NASA TN D-1950

TECHNICAL NOTE

D-1950

RANDOM DEVIATIONS FROM STABILIZED CRUISE ALTITUDES OF COMMERCIAL TRANSPORTS AT ALTITUDES UP TO 40,000 FEET WITH AUTOPILOT IN ALTITUDE HOLD

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON July 1963

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SUMMARY

The random deviations from stabilized cruise altitudes of 19 commercial transports on scheduled, passenger-carrying flights at altitudes up to 40,000 feet have been evaluated from NASA VGH records. The airplanes represented 10 aircraft types of which 4 were turbojets, 3 were turboprops, and 3 were piston engines. They were operated by nine United States airlines for a period of about 1 year over both land and ocean routes covering 9,950 hours of cruise time.

The results of the evaluation showed that the airplanes flew within 200 feet of their stabilized cruise altitude for at least 99.5 percent of the cruise time for operation with autopilot in altitude-hold control and for at least 94.5 percent of the cruise time for operation with manual control. For 0.3 percent of the cruise time, the altitude deviations from stabilized cruise altitudes for operation with autopilot in altitude-hold control did not exceed 250 feet for any of the airplanes over the altitude range up to 40,000 feet. For 0.3 percent of the cruise time, the altitude deviations for manual control were about two to three times those for operation with autopilot in altitude-hold control. No differences in altitude deviations due to altitude, airplane type, airline, route, and season of the year were found.

INTRODUCTION

The amount by which an airplane deviates from its assigned flight level depends not only on the altimeter-system error but also on the random deviations (termed flight technical error in ref. 1) from the actual flight level. Therefore, a measure of these random deviations is needed for any realistic assessment of vertical-separation minimums.

Statistical studies of flight technical errors were performed by the British Ministry of Transport and Civil Aviation (MTCA) in 1957, by the U.S. Civil Aeronautics Administration (CAA) in 1958, and by the National Aeronautics and Space Administration (NASA) in 1961. In the MTCA and CAA tests, the altitude deviations were measured with aircraft altimeters. The measurements were collected for altitudes below 28,000 feet, and the data were evaluated in terms of the altitude deviation that could be expected for a probability of 0.3 percent. In the NASA tests (ref. 2) the measurements were obtained for one airplane with an NASA VGH recorder which provided time histories of the altitude excursions. The data were collected in the altitude range of 20,000 to 41,000 feet, and the results of the study were stated in terms of the altitude deviations at or above which the airplane would be expected to operate for 0.3 percent of the cruise time.

Since the use of time as a criterion for flight technical error in reference 2 is considered to represent a more meaningful measure of collision exposure than the count of altitude deviations used by the MTCA and the CAA, the study of reference 2 has been extended to provide information on additional airplanes operating at altitudes ranging from sea level to 40,000 feet. In the present investigation data were obtained from VGH recorders in 19 civil transports for 9,950 hours of stabilized cruise time over both land and ocean routes.

INSTRUMENTATION

The instruments used to evaluate the altitude deviations from stabilized cruise altitudes were NASA VGH recorders, which provide a continuous time history of indicated airspeed, pressure altitude, and normal acceleration. The recording paper is driven at a rate of about 0.5 inch per minute and is marked by a timer at 1-minute intervals. A description of these instruments is given in reference 3.

For each instrument installation the airspeed and altitude elements were connected to one of the service pitot-static systems of the airplane, and the accelerometer transducer was located in the vicinity of the airplane center of gravity. The sensitivity of the altitude elements varied from about 8,000 feet per inch of recording paper at sea level to about 25,000 feet per inch of recording paper at 40,000 feet.

AIRPLANES AND OPERATIONS

Airplanes

The 19 airplanes for which altitude deviations were evaluated in the present investigation were all passenger-carrying commercial transports representing 10 aircraft types of which 4 were turbojets, 3 turboprops, and 3 piston engines. Some of the physical characteristics such as maximum gross weight, wing area, and wing span of the 10 transport types are given in table I. Because of the large differences between the two models of type I airplanes, IA and IC transports are considered to be different types. It should be noted that airplane IA is the airplane for which data were reported in reference 2. Each of the airplanes was equipped with an autopilot which could be operated in either the attitude-hold or the altitude-hold control mode.

Operations

Each of the 19 airplanes was operated by one of nine major United States airlines on scheduled, passenger-carrying flights through some portion of the altitude range up to 40,000 feet. The airplanes were flown over a number of different routes which included the Pacific Ocean, United States, Atlantic Ocean, Western Europe, and South America. For the 19 airplanes, data were obtained from 8,394 flights covering 9,950 hours of stabilized cruise time.

All the airplanes were operated with the autopilot in altitude-hold control during those portions of cruise flight for which the altitude deviations were evaluated in the present investigation. In addition, four of these airplanes were operated for periods of time with manual control exclusively, and the altitude deviations were evaluated for these periods of time. The operational variables such as airplane type, airline, type of control, air route, data collection period, hours of stabilized cruise operation, and number of flights for each of the 19 airplanes are given in table II.

DATA SAMPLING, EVALUATION, AND ACCURACY

Data Sampling

In general, VGH records covering about 1 year were used as data samples (table II) in order to determine any possible variation in altitude deviation with season. In addition, the flight records for all of the turbojets, with the exception of the airplane of reference 2, covered about the same time period.

For an evaluation of the data obtained with the autopilot in altitude-hold control, the flight records were examined to eliminate those portions of the cruise operation when the airplanes were flown under manual control or with the autopilot in attitude-hold control. The type of control-mode operation was determined from an inspection of the airspeed, altitude, and, particularly, the acceleration traces of the VGH record since the normal acceleration exhibits a characteristic response for each of the different control modes. The data obtained during operation with the autopilot in altitude hold were selected for evaluation because this control mode is the most precise means for maintaining constant altitude. All the available records for each of the airplanes, which was operated with the autopilot in altitude hold during the time periods shown in table II, were evaluated. In addition, the records from four of these airplanes, which were operated continuously with manual control during the periods indicated in table II, were evaluated. A reexamination of the records used in reference 2 disclosed the fact that some of these records were obtained when the airplane was operated with manual control or with the autopilot in attitude hold. The records from that investigation were therefore reevaluated in the present study to include only those applying to operation with the autopilot in attitude hold.

The acceleration records of three airplanes for which long-term data were available were evaluated to determine whether the atmospheric turbulence level that prevailed during the flights of the present study was representative of the turbulence level that was experienced over the much longer period. For altitudes ranging from sea level to 25,000 feet, accelerometer-record evaluations showed that gust accelerations for the flights of the present study were in fact comparable to those for the longer period of time. Inasmuch as the turbulence level up to 25,000 feet for the present data is comparable to the long-term turbulence level, it would appear reasonable to assume that the turbulence level from 25,000 to 40,000 feet for the present data will also be comparable.

Data Evaluation

In the evaluation of the VGH recordings of the altitude deviations, measurements were made of the time intervals within each deviation at successive 100-foot altitude increments from stabilized cruise altitude. The stabilized cruise altitude was determined as the altitude at the start of cruise flight where the recordings of both airspeed and altitude had stabilized to constant values. On flights in which the airplane changed flight level, a new reference altitude was established for evaluating the succeeding altitude deviations.

For the measurements of the time intervals within the altitude deviations, use was made of a specially designed optical reader through which the VGH record was traversed a number of times. For each traversal, the horizontal cross hair of the reader was adjusted to a setting corresponding to a given altitude increment (100, 200, 300 feet, etc.) from the setting for stabilized cruise altitude. Thereafter, as the record was moved through the reader, a linear measuring device consisting of a rubber roller connected to a digital counter was engaged whenever the vertical cross hair intersected the ascending portion of an altitude deviation and was disengaged when the cross hair intersected the descending portion. The final reading of the counter for each traverse thus provided a linear measurement from which the corresponding time period could be determined.

This measuring procedure is illustrated in figure 1 which shows an illustration of four altitude deviations from the stabilized cruise altitude. The values of Δd_{100} within each of the four deviations are the distances along the recording paper at a vertical displacement corresponding to an altitude increment of 100 feet above and below the stabilized cruise altitude. From measurements of the time scale on the recording paper and values of Δd_{100} as measured by the counter, the time interval t_{100} at the altitude increment of 100 feet was determined. The time intervals at the higher altitude increments (200, 300 feet, etc.) were determined in the same manner. Finally, from the values of the time periods at each altitude increment and a measure of the length of time t_c the airplane flew at its stabilized cruise altitude, computations of the percent of cruise time ($t/t_c \times 100$) at each altitude increment were made. These data were grouped for each airplane according to the altitude bracket, in increments of 5,000 feet from sea level, in which the airplane cruised, and plots were made of the percent of stabilized cruise time spent at or above the various altitude deviations. Since these plots provide no indication whether the altitude deviations were above or below the cruise altitude, it should be noted that an evaluation of the data for a number of airplanes showed that the distribution of deviations above the cruise altitude was about equal to that below the cruise altitude. In conformity with the altitude-deviation criterion introduced in reference 2, the present data are compared in terms of the altitude deviations for 0.3 percent of the stabilized cruise time.

Data Accuracy

The accuracy of the altitude increment, based on the sensitivity of the altitude measuring elements of the VGH recorder and the accuracy of the readout, varied from about ±8 feet at sea level to about ±25 feet at 40,000 feet. The accuracy of the time-interval measurement, based on the accuracy of the timer and the reading accuracy of the optical measuring device and counter, was about ±0.1 minute.

The validity of the data depends not only on the accuracy of the altitude-increment and time-interval measurements but also on the size of the data sample (that is, the number of hours of stabilized cruise time). In order to determine any variation in the data due to sample size, the number of hours for nine large data samples was decreased initially by deleting every third record; then, every other record of those remaining was deleted, and, finally, again every other record of those remaining was deleted. Thus, the number of hours for each case was decreased from about 300 hours to about 200, 100, and 50 hours, respectively. A comparison between the deviations for 0.3 percent of the stabilized cruise time for the nine large samples and those for the reduced samples showed maximum variations of 25, 50, and 80 feet for the sample sizes of 200, 100, and 50 hours, respectively.

RESULTS AND DISCUSSION

The results of the evaluation of the altitude deviations of the 19 transports are presented in figures 2 and 3. Figures 2(a) to 2(s) apply to operations with autopilot in altitude-hold mode whereas figures 3(a) to 3(d) apply to operations under manual control. The data are presented in terms of the percent of cruise time the airplanes flew at or above various altitude deviations in increments of 100 feet from stabilized cruise altitude. For each of the figures the data have been grouped in altitude brackets of 5,000 feet and for each of the altitude brackets the size of the data sample is given in terms of the number of hours of cruise flight. Also indicated is the 0.3-percent point along the percent-of-cruise-time scale.

In the fairing of the curves through the data points, more emphasis was given to those points for which the percent of cruise time was highest since the accuracy of these points should be greater. The curves were not extended beyond those points for which the time period was less than 0.5 minute, that is, a period five times the estimated accuracy of the time-interval measurement; these points are denoted in figures 2 and 3 by the flagged symbols.

The data in figures 2(a) to 2(s) show that for operation with the autopilot in altitude-hold control the airplanes in all cases flew for at least 99.5 percent of the cruise time within 200 feet of their stabilized cruise altitude. The data also show that the largest altitude deviation for the present data was 1,700 feet (fig. 2(r)). The data in figures 3(a) to 3(d) show that for operation with manual control the airplanes flew for at least 94.5 percent of the cruise time within 200 feet of their stabilized cruise time.

The altitude deviations for 0.3-percent cruise time for the 19 airplanes operating with autopilot in altitude-hold control are plotted in figure 4 at the middle of the 5,000-foot altitude bracket in which the values were determined. The data indicate that there is no significant variation of altitude deviations with altitude up to 40,000 feet. The data also indicate that there is no effect of airplane type on the altitude deviations. The most important result shown by this figure is that the altitude deviations did not exceed 250 feet for any of the airplanes over the altitude range. A comparison of the data for airplane IC (case 2) operated by airline E with the data for airplane IC (case 3) operated by airline F over predominantly water routes indicated no effect of airline on altitude deviation. Similarly, a comparison of the data for airplane IIB (cases 4 and 5) operated by airline C with data for airplane IIB (case 6) operated by airline G over the United States showed no effect of airline on altitude deviation.

Figure 5 shows the altitude deviations for 0.3 percent of stabilized cruise time for five pairs of airplanes where for each pair the airplane type, airline, route, and data collection period were the same. The data show that for a pair of airplanes, where the variables that can affect the altitude deviations were the same, there were differences in altitude deviations up to 140 feet. The mean difference in altitude deviations for all five pairs was about 60 feet, so that differences in altitude deviations for any variable must exceed 60 feet in order to be considered significant.

The differences in altitude deviations for 0.3 percent of the stabilized cruise time resulting from operation with manual control and with autopilot in altitude-hold control for two pairs of airplanes are shown in figure 6. The data show that for each altitude bracket the altitude deviations for manual control are about two to three times those for autopilot in altitude-hold control.

Although not shown, the data for each airplane and altitude bracket were grouped according to season of the year, and no effect of season on altitude deviation was shown. Grouping of the data for the various airplanes according to the geographic area over which they were flown, and grouping of all the data on the basis of operation over land or water showed no effect of route on altitude deviation.

CONCLUSIONS

An evaluation has been made of the random deviations from stabilized cruise altitudes of 19 commercial transports representing 10 aircraft types operated by 9 U.S. airlines and flown in general for a period of about 1 year over both land and water routes. An analysis of 9,950 hours of cruise time for the altitude range from sea level up to 40,000 feet showed:

1. The airplanes flew within 200 feet of their stabilized cruise altitude for at least 99.5 percent of the cruise time for operation with autopilot in altitude-hold control and for at least 94.5 percent of the cruise time for operation with manual control.

2. For 0.3 percent of the cruise time, the altitude deviations from stabilized cruise altitudes for operation with autopilot in altitude-hold control did not exceed 250 feet for any of the airplanes over the altitude range up to 40,000 feet.

3. For 0.3 percent of the cruise time, the altitude deviations from stabilized cruise altitude for operation with manual control were two to three times those for operation with autopilot in altitude-hold control.

4. No differences in altitude deviations due to altitude, airplane type, airline, route, and season of the year were found.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., June 5, 1963.

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2. Gracey, William, and Shipp, Jo Ann: Random Deviations From Cruise Altitudes of a Turbojet Transport at Altitudes Between 20,000 and 41,000 Feet. NASA TN D-820, 1961.

3. Richardson, Norman R.: NACA VGH Recorder. NACA TN 2265, 1951.

TABLE I.- AIRPLANE CHARACTERISTICS

Airplane type (a)	Airplane model	Propulsion	Maximum gross weight, lb	Wing area, sq ft	Wing span, ft
I	A	Turbojet	248,000	2,433	130.8
	C	Turbojet	316,000	2,892	142.4
II	B	Turbojet	276,000	2,771	142.4
	C	Turbojet	310,000	2,771	142.4
III	A	Turbojet	189,500	2,000	120.0
IV	A	Turboprop	116,000	1,300	99.0
V	A	Turboprop	37,500	754	95.2
VI	A	Turboprop	64,500	963	93.7
X	---	Piston engine	93,200	1,463	117.5
XI	---	Piston engine	122,000	1,463	117.5
XII	---	Piston engine	147,000	1,720	141.3

[a]Models A and C of type I are considered to be different airplane types.

TABLE II.- GENERAL OPERATIONAL DATA

Case	Airplane	Airline	Type of control (a)	Route	Data collection period	Stabilized cruise hours	Number of flights
1	IA	E	Autopilot	North Atlantic Ocean, Western Europe	Jan. 1959 to Aug. 1959	438	195
2	IC	E	Autopilot	North Pacific Ocean	July 1960 to July 1961	695	228
3	IC	F	Autopilot	United States, North Atlantic Ocean, Western Europe	July 1960 to July 1961	829	296
4	IIB	C	Autopilot	Eastern United States	June 1960 to Mar. 1961	514	365
5	IIB	C	Autopilot	Eastern United States	May 1960 to Dec. 1961	288	221
6	IIB	G	Autopilot	United States	July 1960 to June 1961	361	155
7	IIC	E	Autopilot	North Atlantic Ocean, Western Europe	July 1960 to July 1961	751	311
8	IIC	E	Autopilot	North Atlantic Ocean, Western Europe, South America	Sept. 1960 to May 1961	298	148
9	IIIA	I	Autopilot	United States	July 1960 to Apr. 1961	442	241
10	IIIA	I	Manual	United States	Aug. 1961 to Jan. 1962	236	456
11	IIIA	I	Autopilot	United States	June 1960 to Jan. 1961	355	201
12	IIIA	I	Manual	United States	Feb. 1961 to Dec. 1961	215	406
13	IVA	A	Autopilot	United States	July 1959 to Apr. 1960	565	798
14	IVA	A	Manual	United States	Apr. 1960 to Jan. 1961	333	446
15	IVA	A	Autopilot	United States	Jan. 1962 to Nov. 1962	159	328
16	IVA	A	Manual	United States	Mar. 1960 to Mar. 1961	488	665
17	VA	J	Autopilot	Eastern United States	Feb. 1959 to Dec. 1960	153	784
18	VA	J	Autopilot	Eastern United States	Feb. 1959 to Mar. 1961	161	833
19	VIA	L	Autopilot	Eastern United States	May 1957 to Sept. 1958	447	577
20	X	D	Autopilot	Eastern United States	Aug. 1954 to Aug. 1955	333	243
21	XI	D	Autopilot	Eastern United States	Mar. 1957 to Apr. 1958	332	201
22	XII	G	Autopilot	United States	Jan. 1953 to Sept. 1953	894	115
23	XII	E	Autopilot	North Atlantic Ocean, Western Europe	Dec. 1953 to Dec. 1954	663	181

[a]All autopilot control is with autopilot in altitude-hold mode.

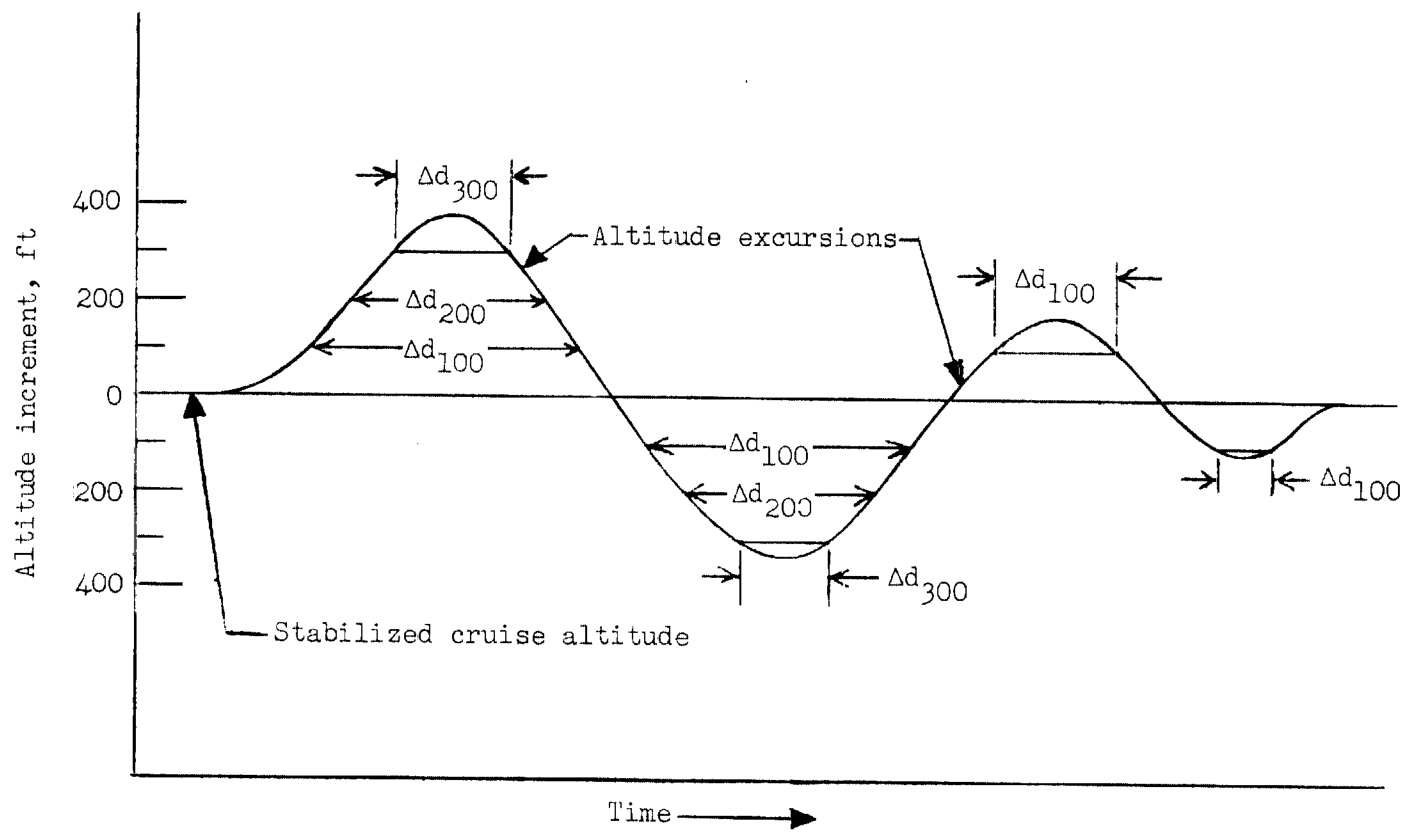
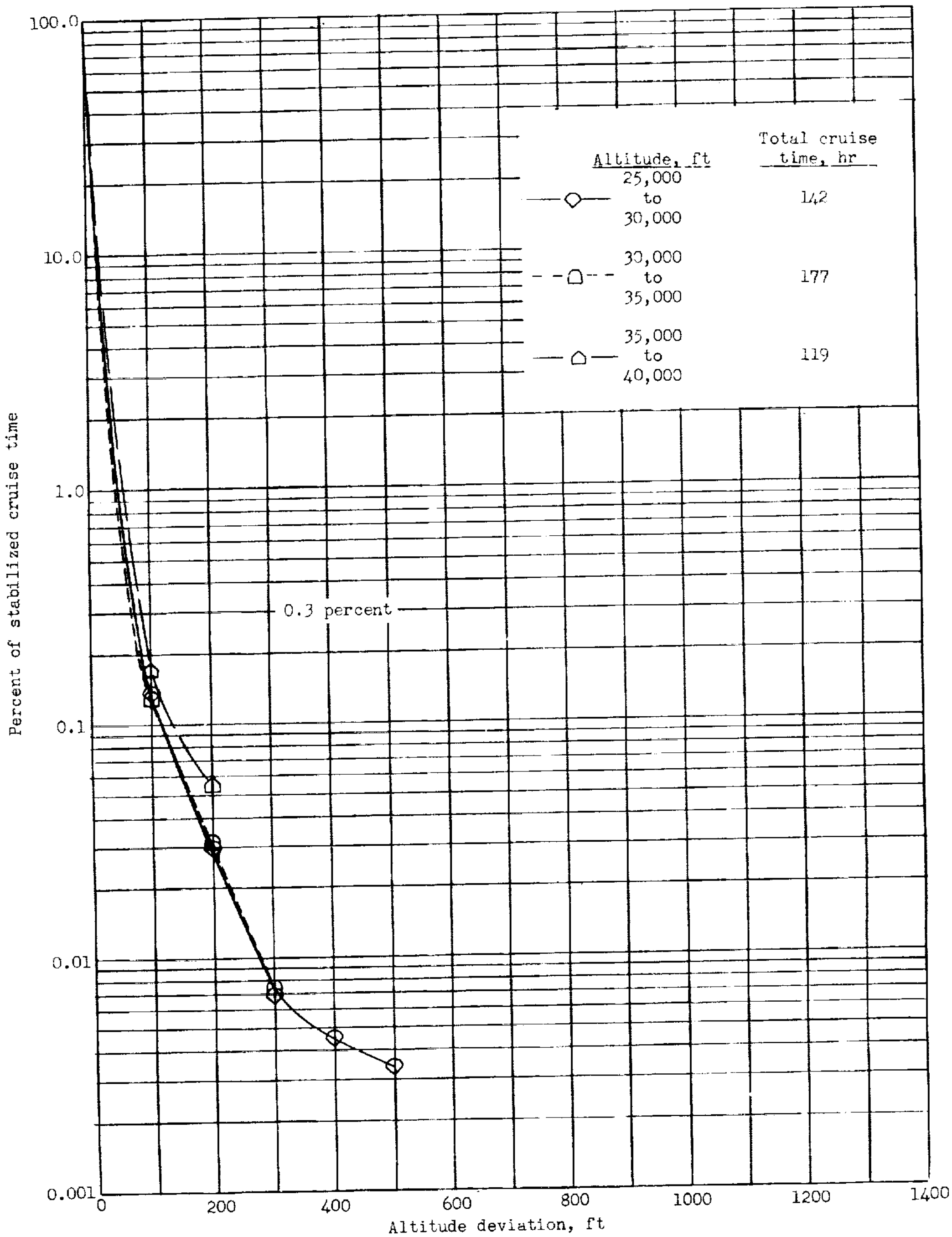
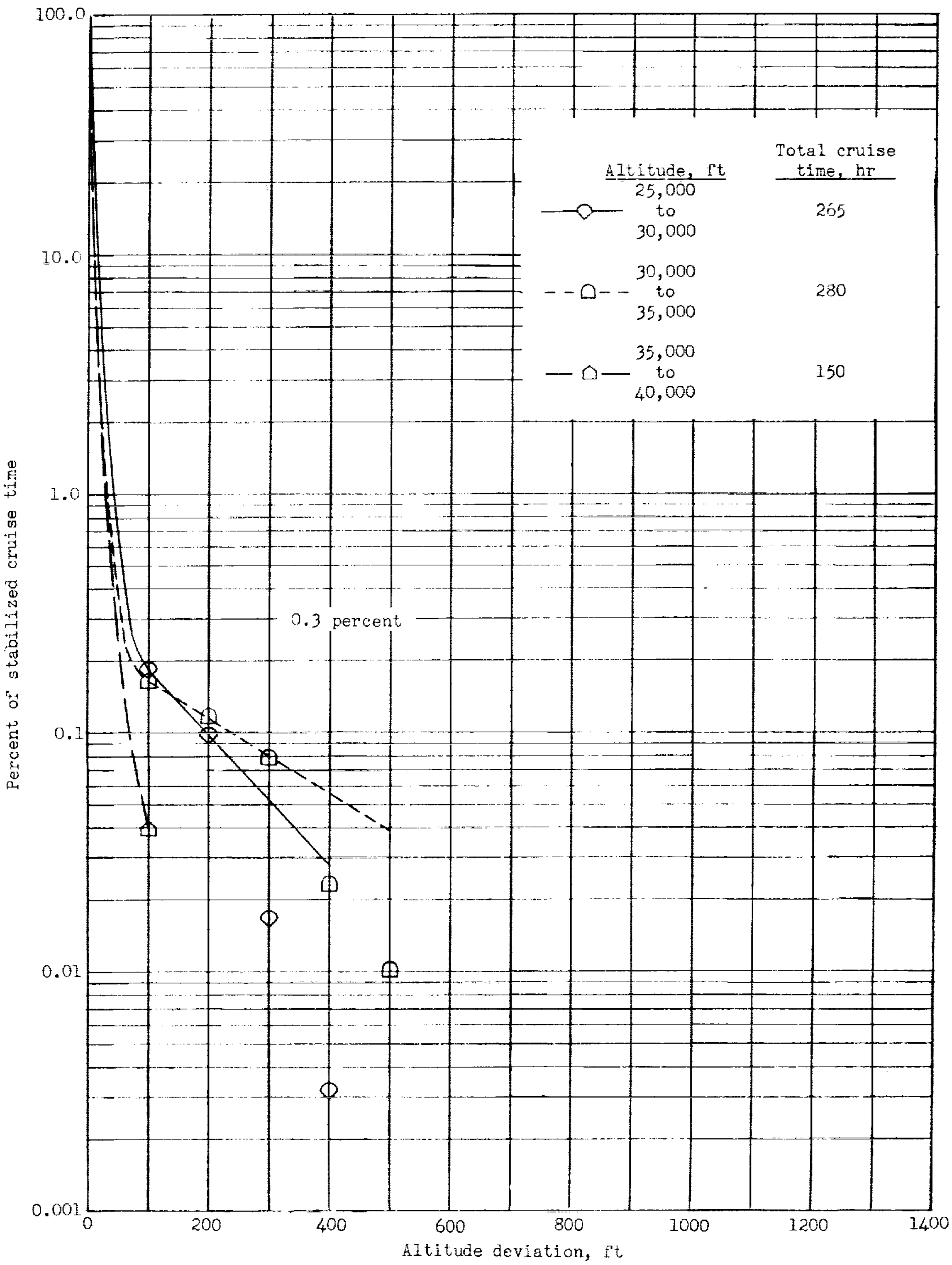


Figure 1.- Illustration of method of measuring time intervals, within altitude excursions, at 100-foot increments from stabilized cruise altitude. Δd is distance along VGH record at given altitude increments.



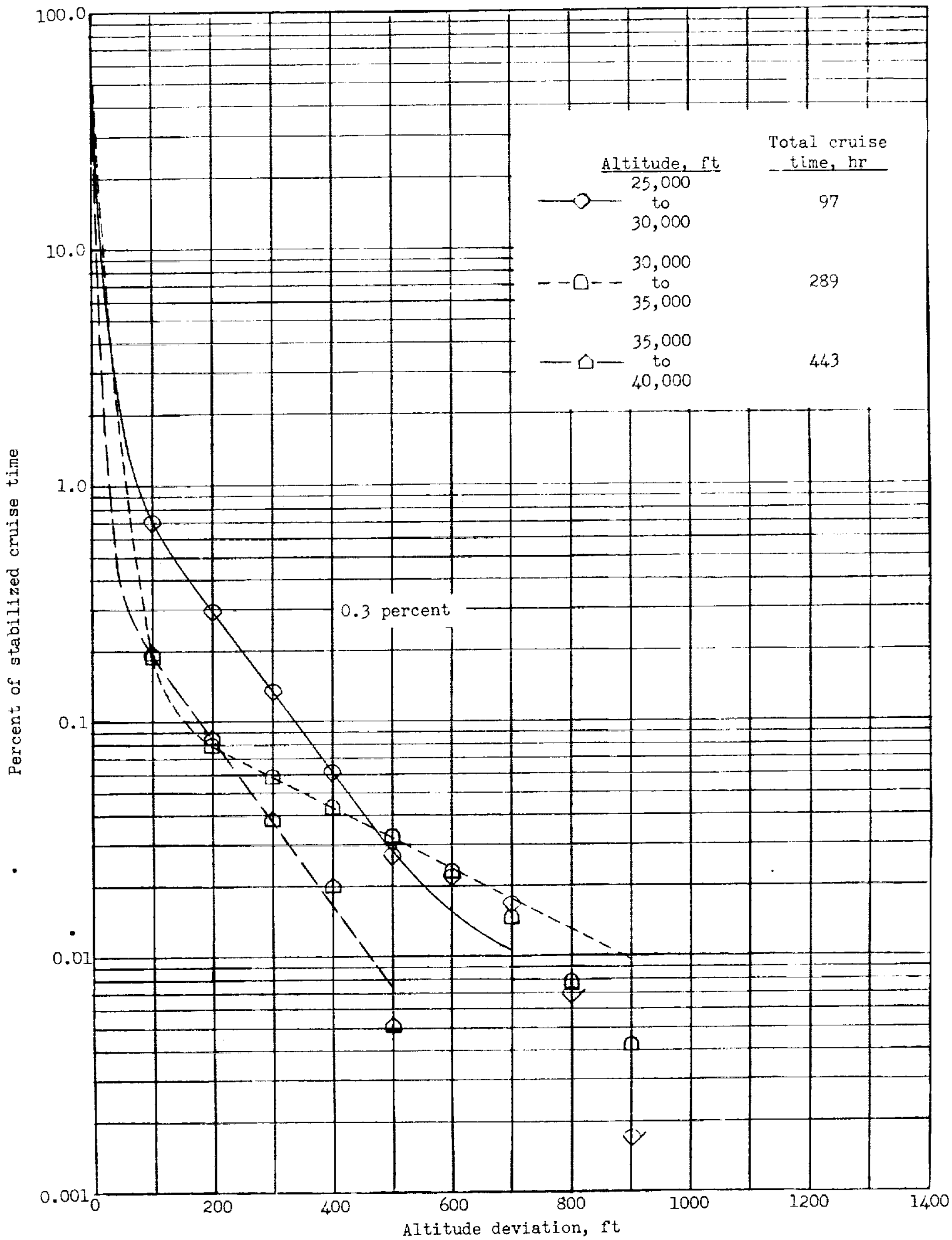
(a) Airplane IA; case 1.

Figure 2.- Percent of stabilized cruise time airplanes flew at or above various altitude deviations from stabilized cruise altitude with autopilot in altitude-hold control. Flagged symbols denote data points for which time period was less than 0.5 minute.



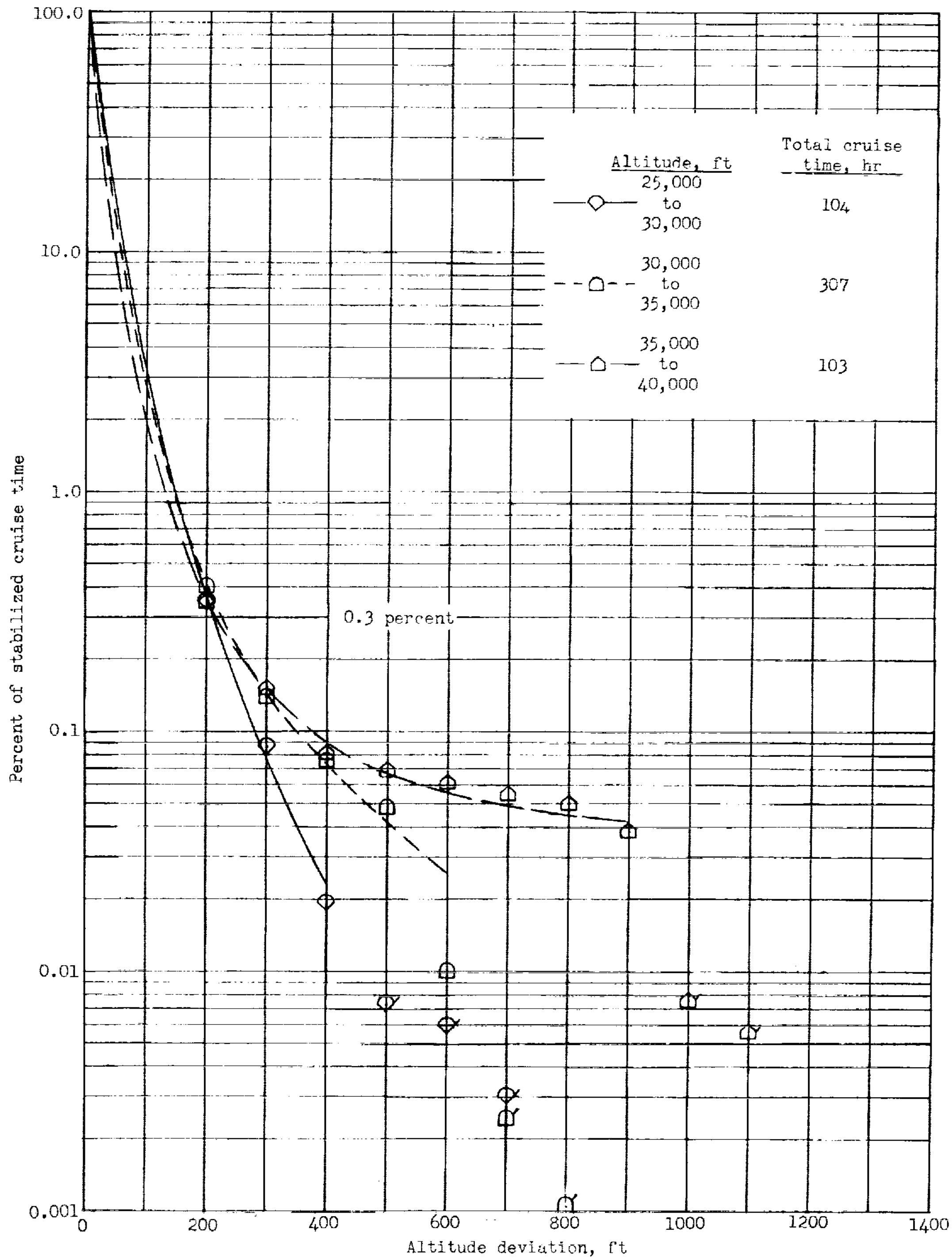
(b) Airplane IC; case 2.

Figure 2.- Continued.



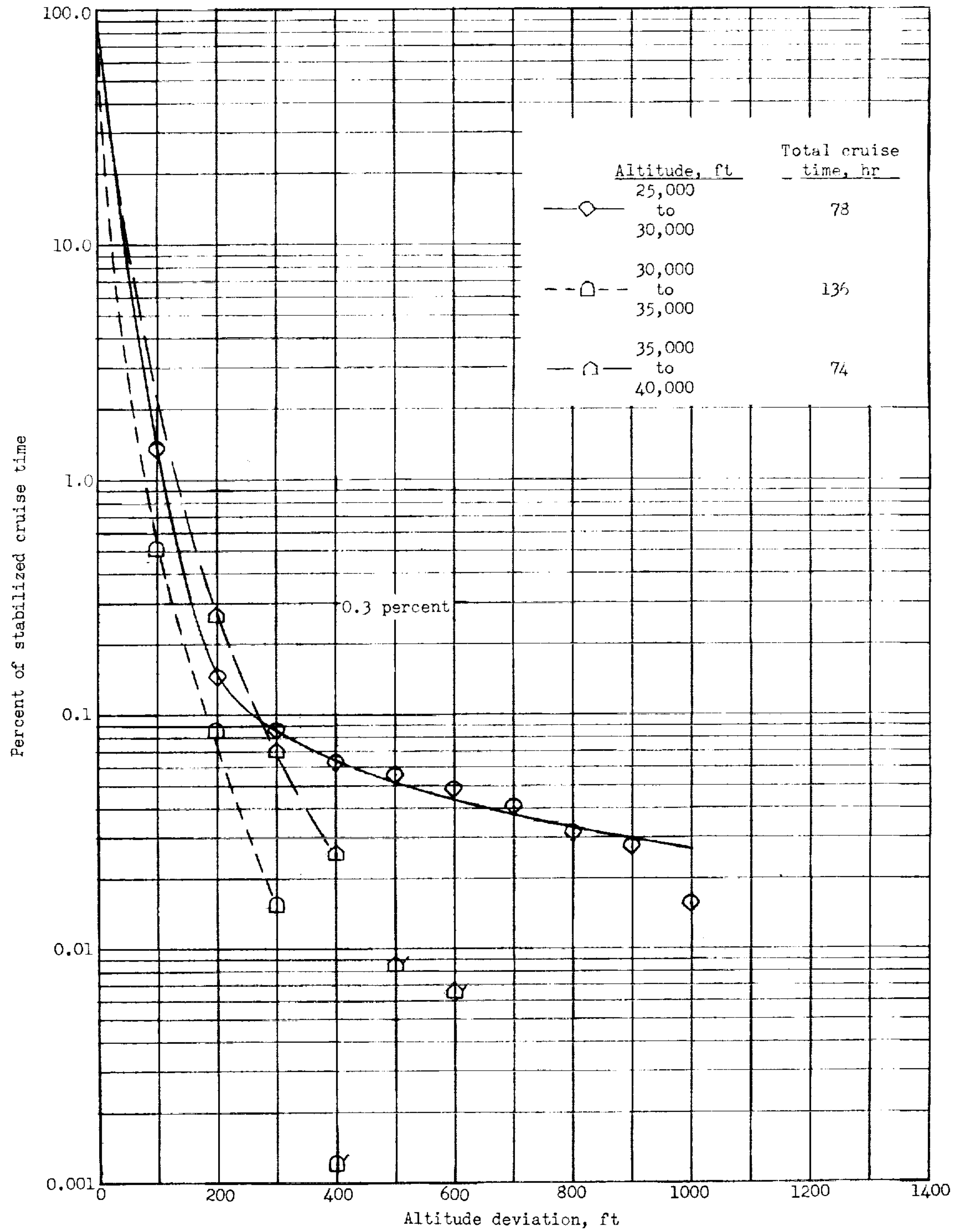
(c) Airplane IC; case 3.

Figure 2.- Continued.



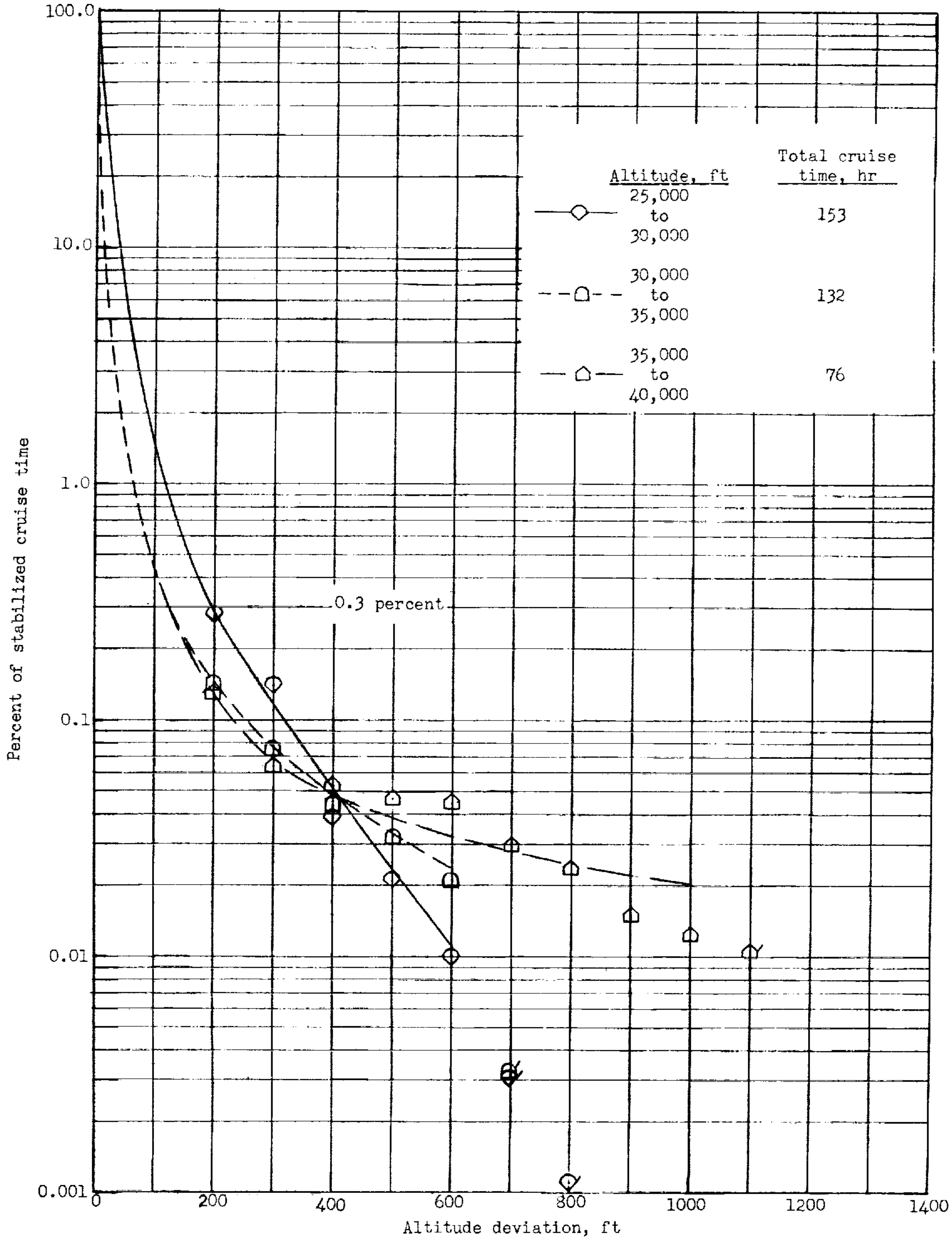
(d) Airplane IIB; case 4.

Figure 2.- Continued.



(e) Airplane IIB; case 5.

Figure 2.- Continued.



(f) Airplane IIB; case 6.

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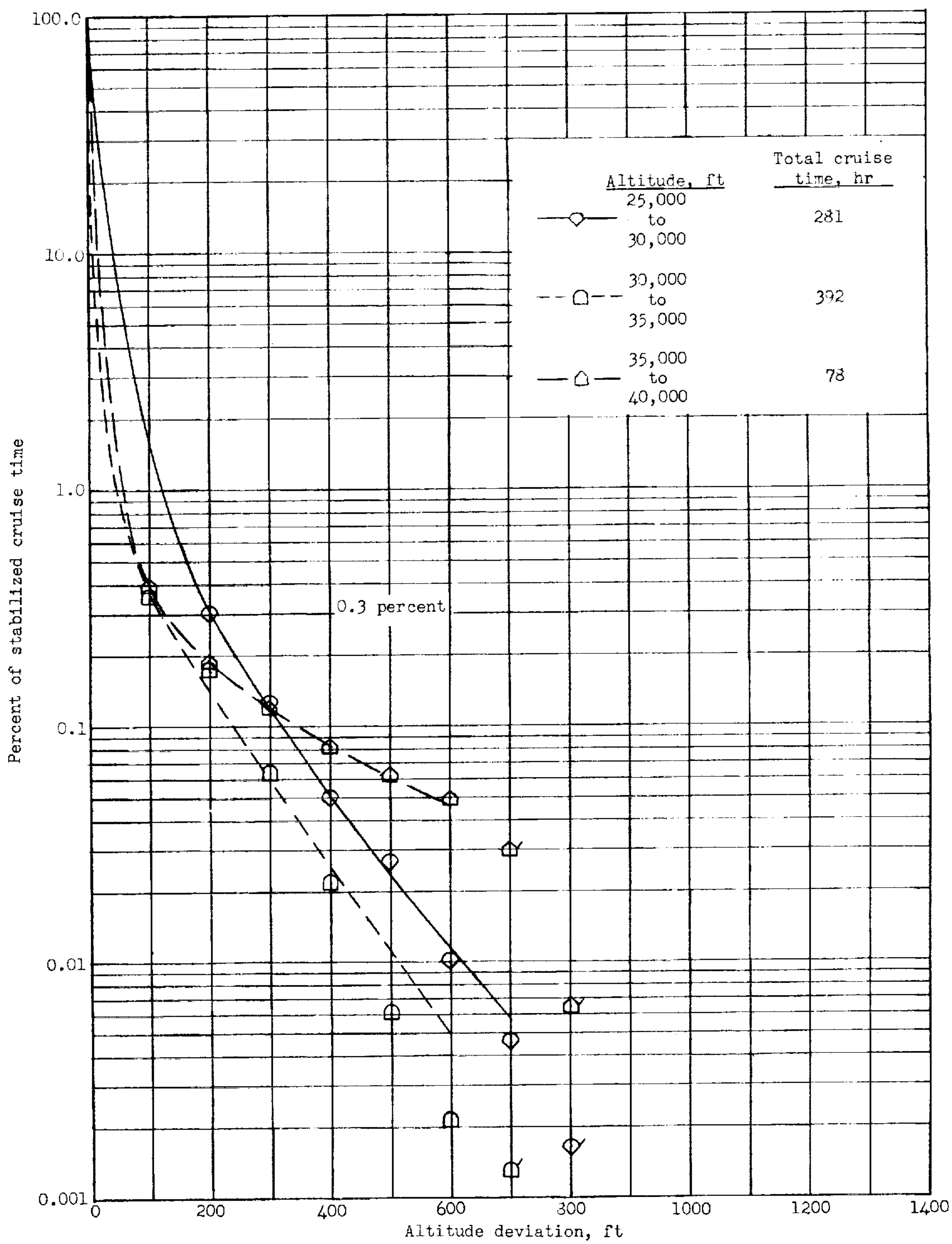

(g) Airplane IIC; case 7.

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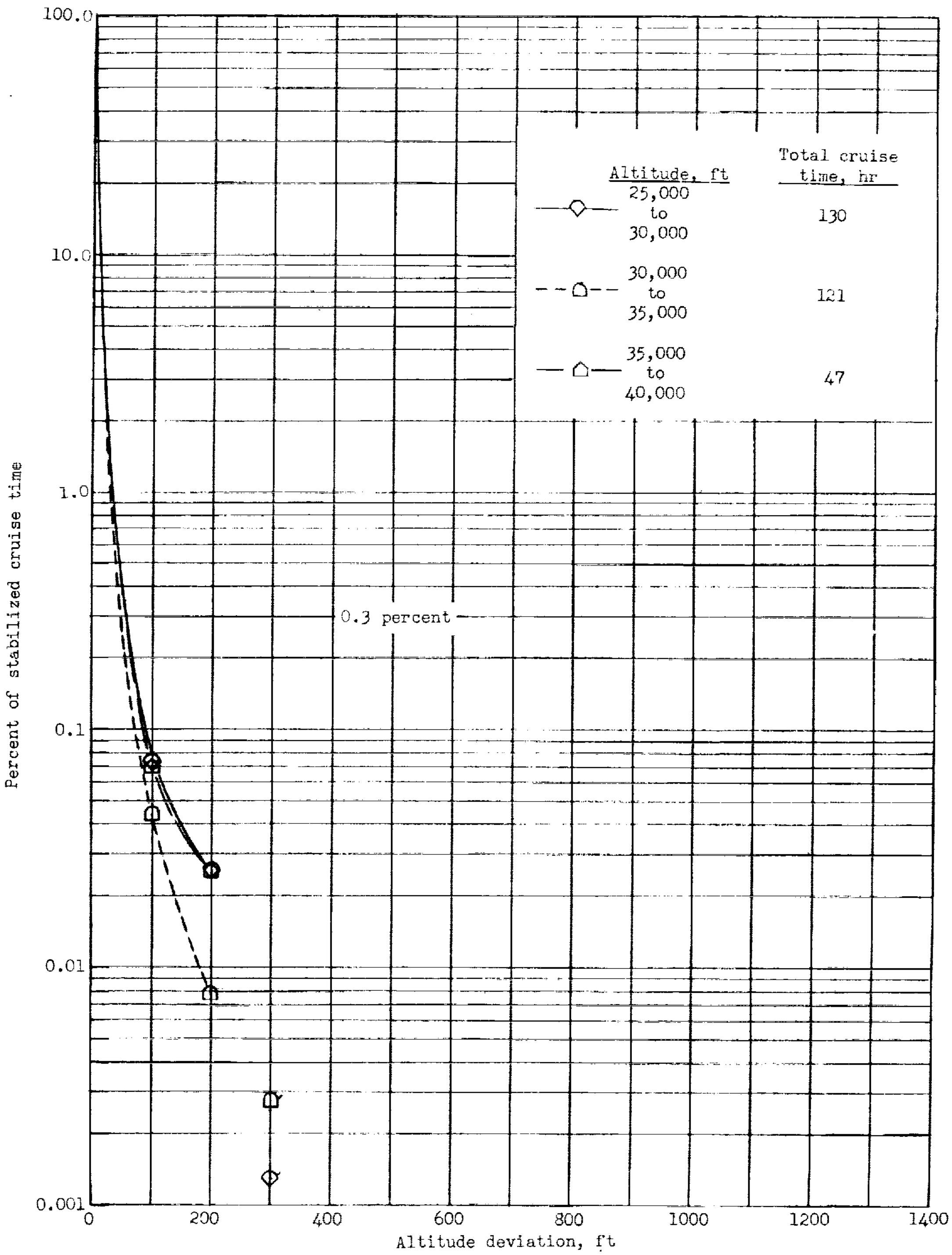

(h) Airplane IIC; case 8.

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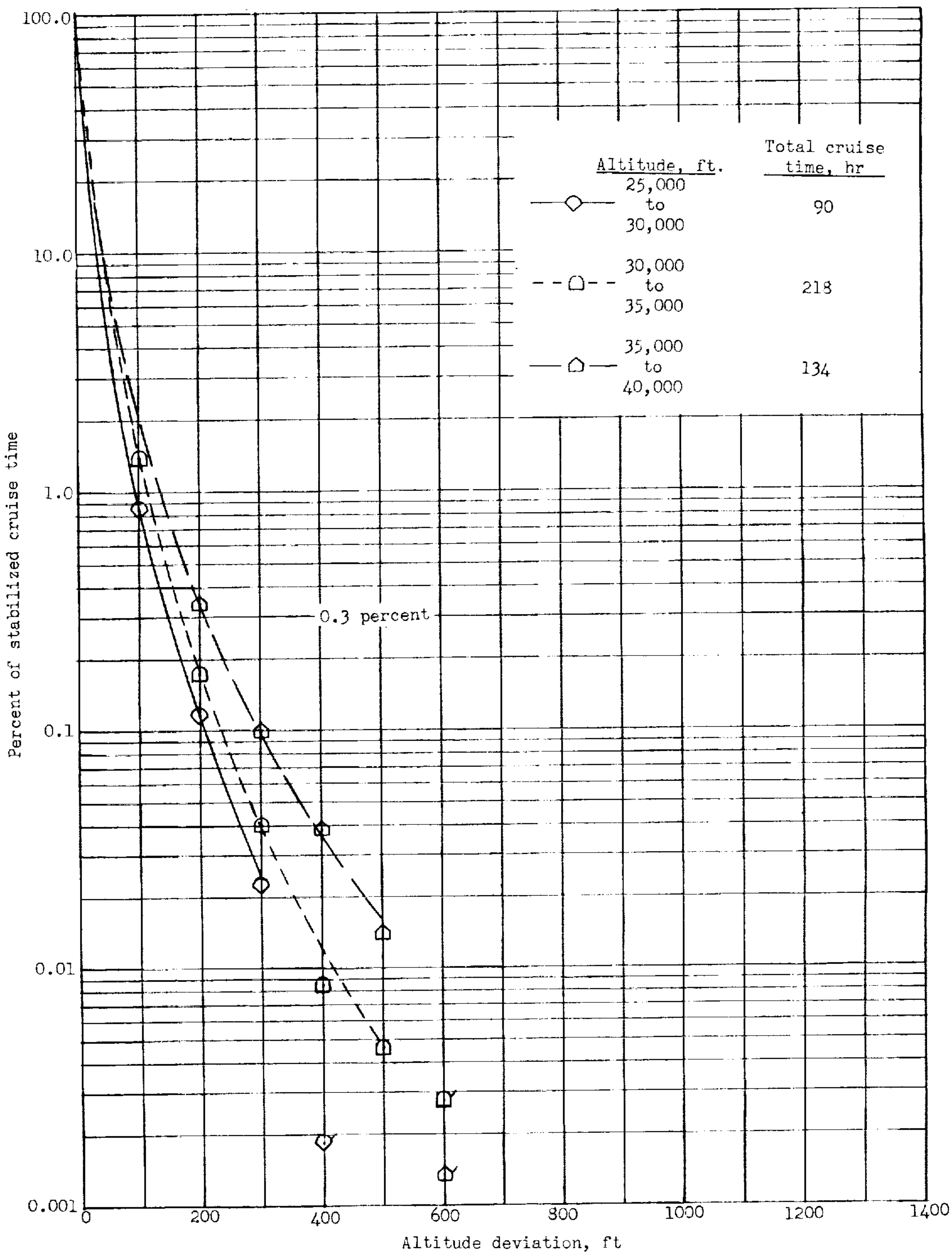

(i) Airplane IIIA; case 9.

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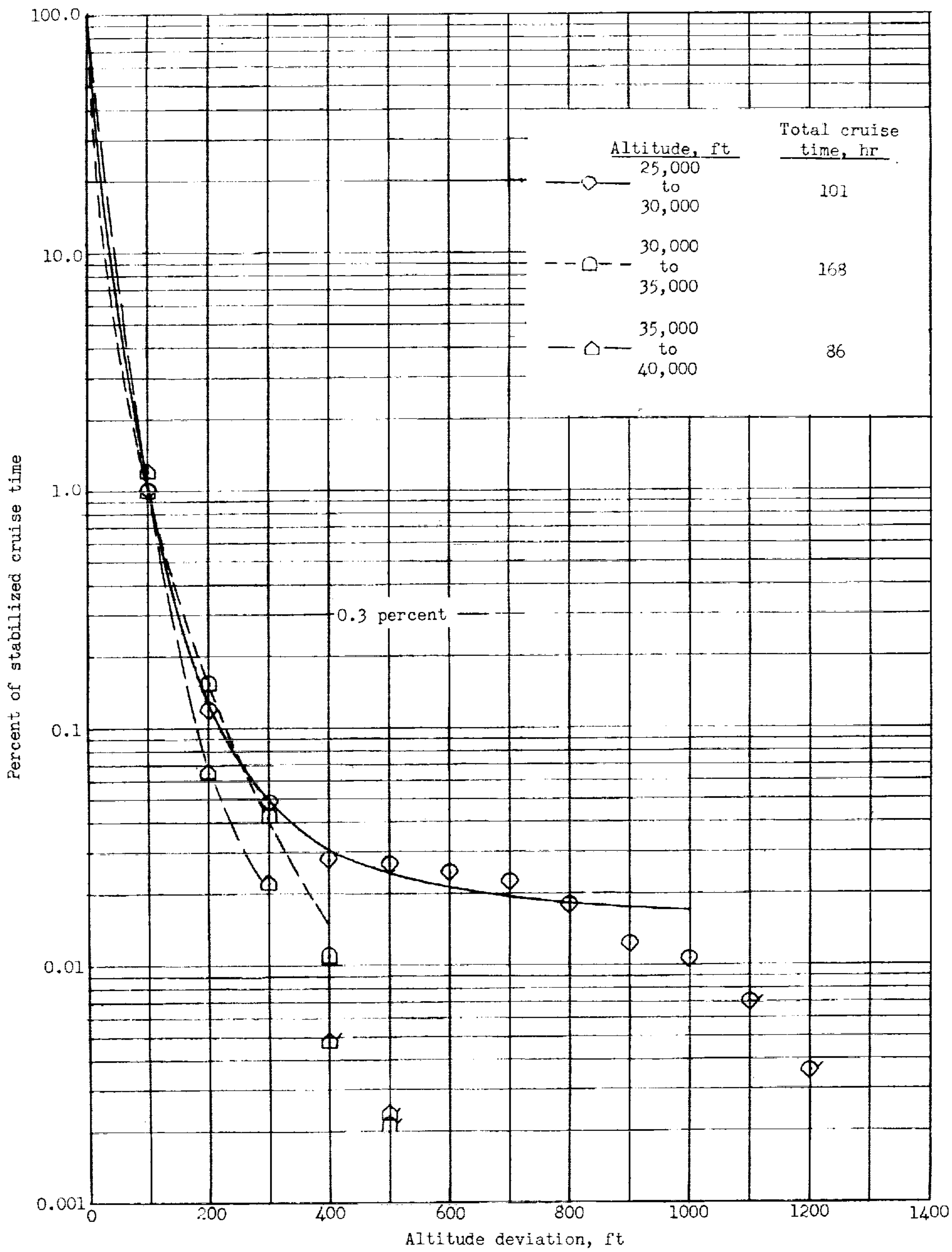

(j) Airplane IIIA; case 11.

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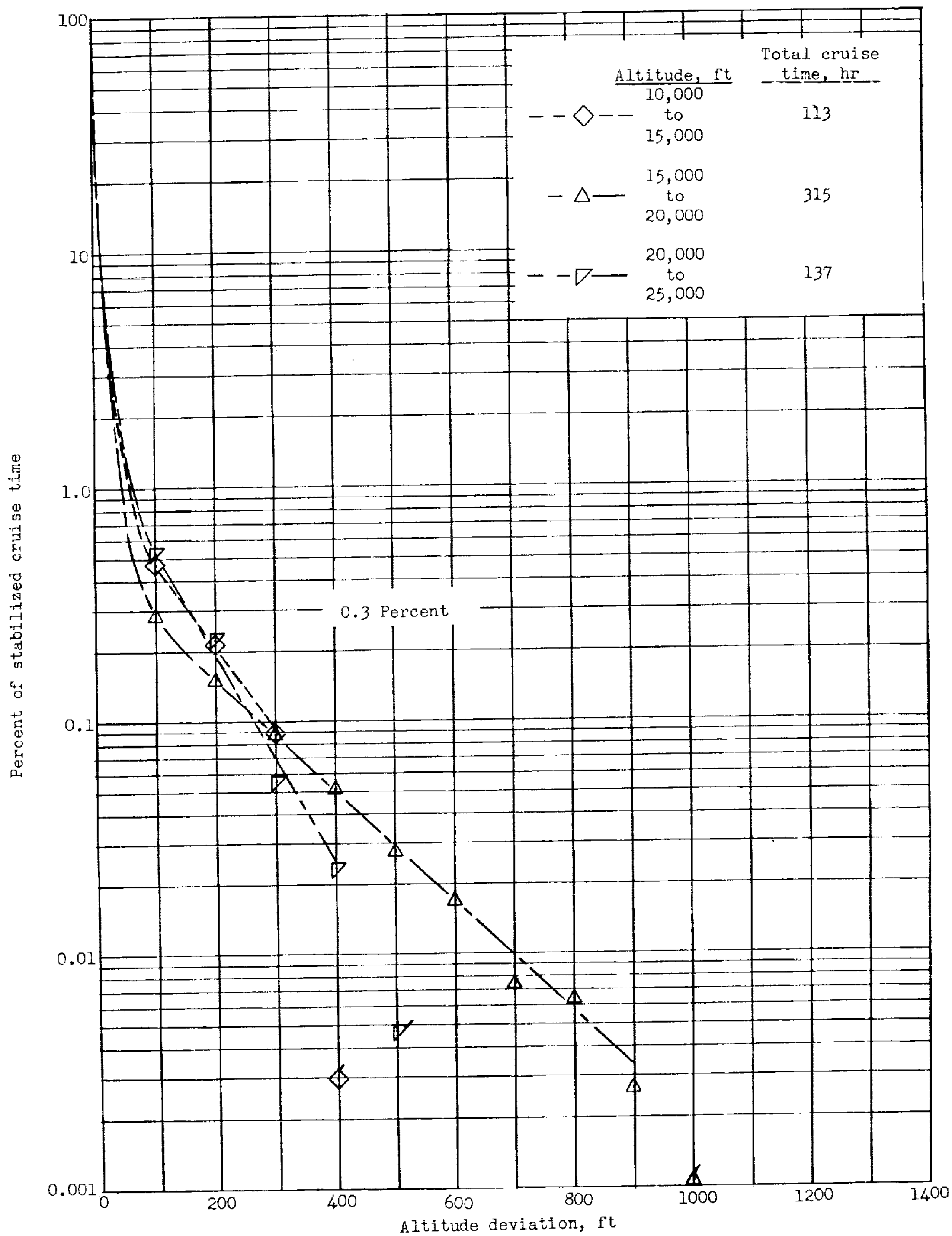
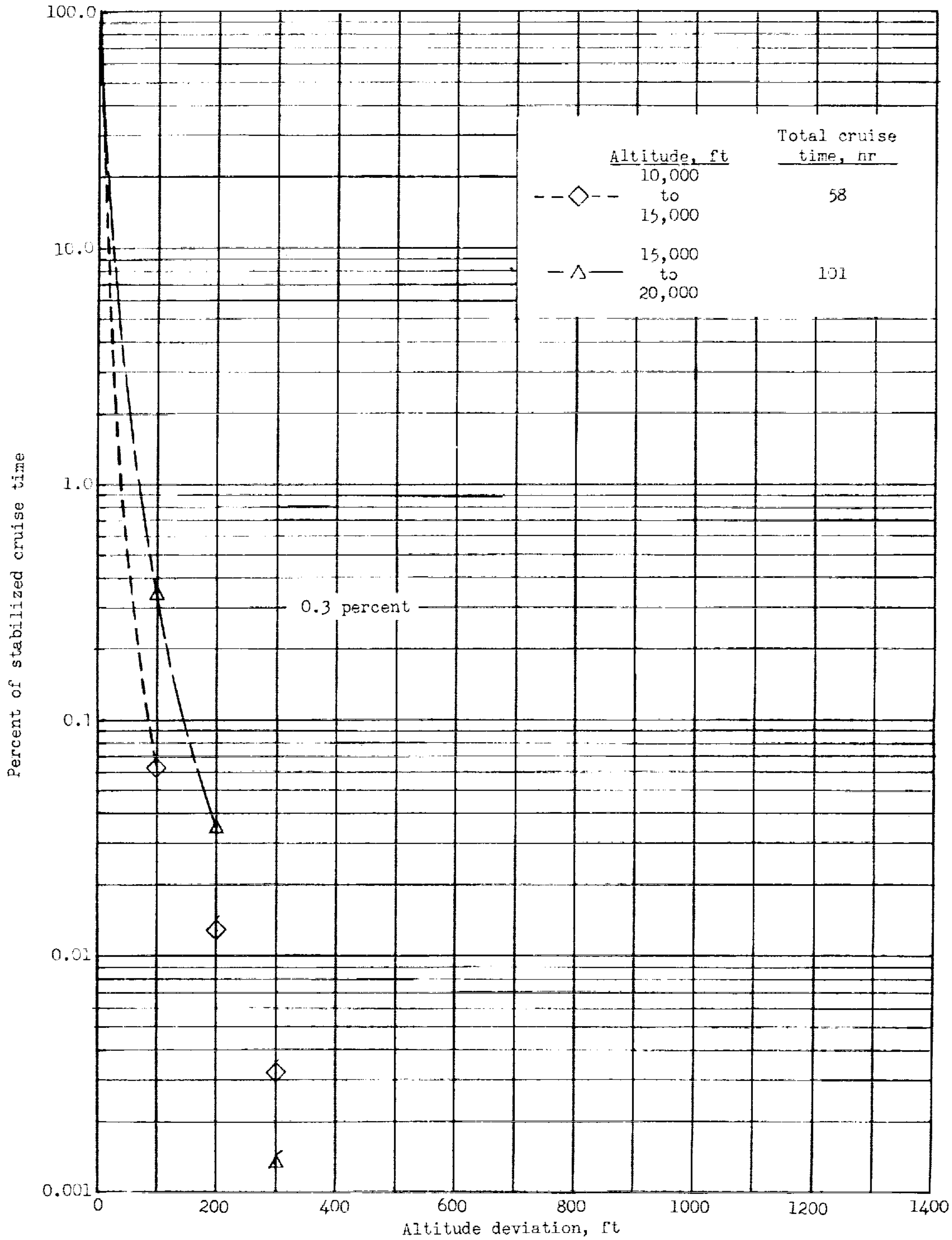


(k) Airplane IVA; case 13.

Figure 2.- Continued.



(l) Airplane IVA; case 15.

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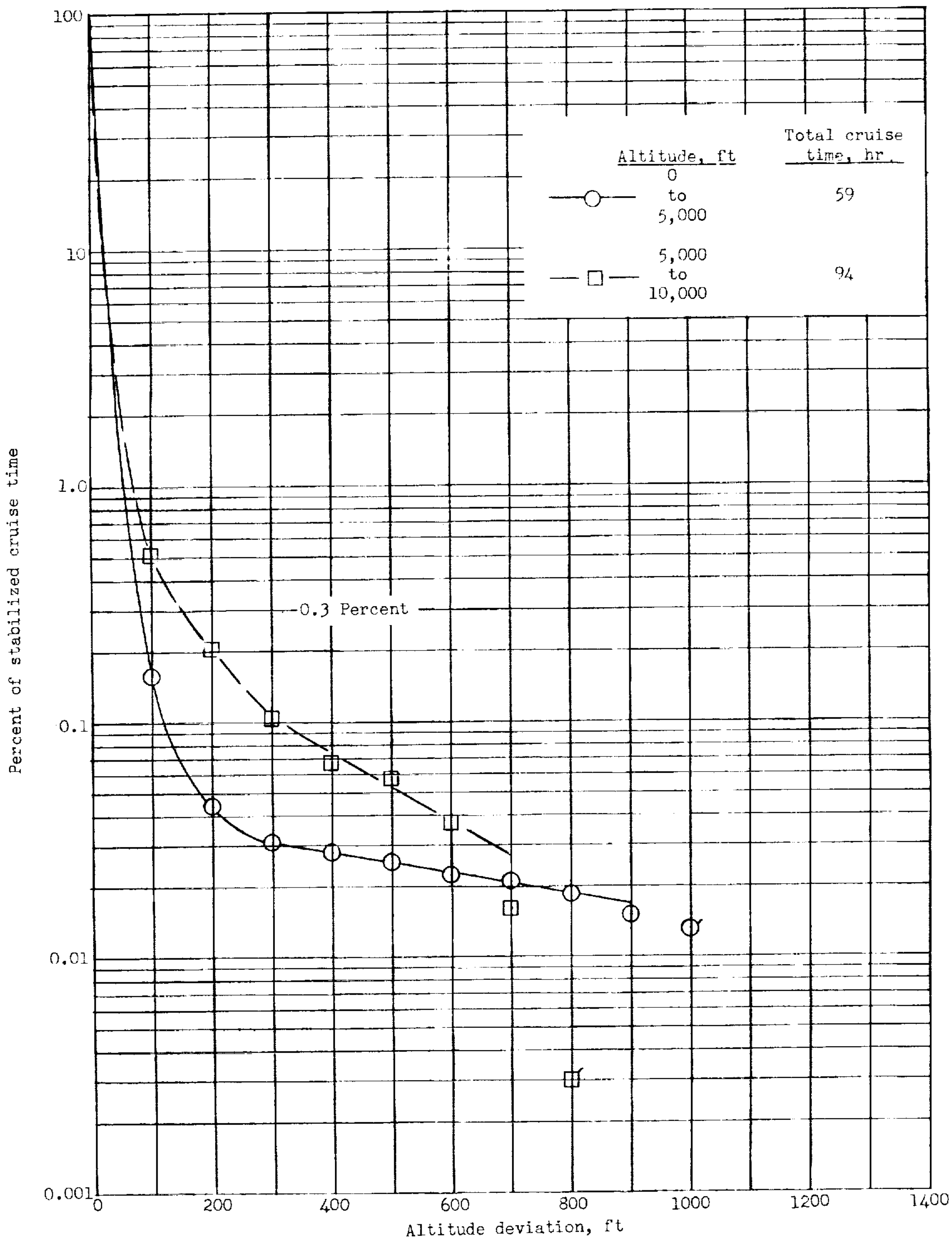

(m) Airplane VA; case 17.

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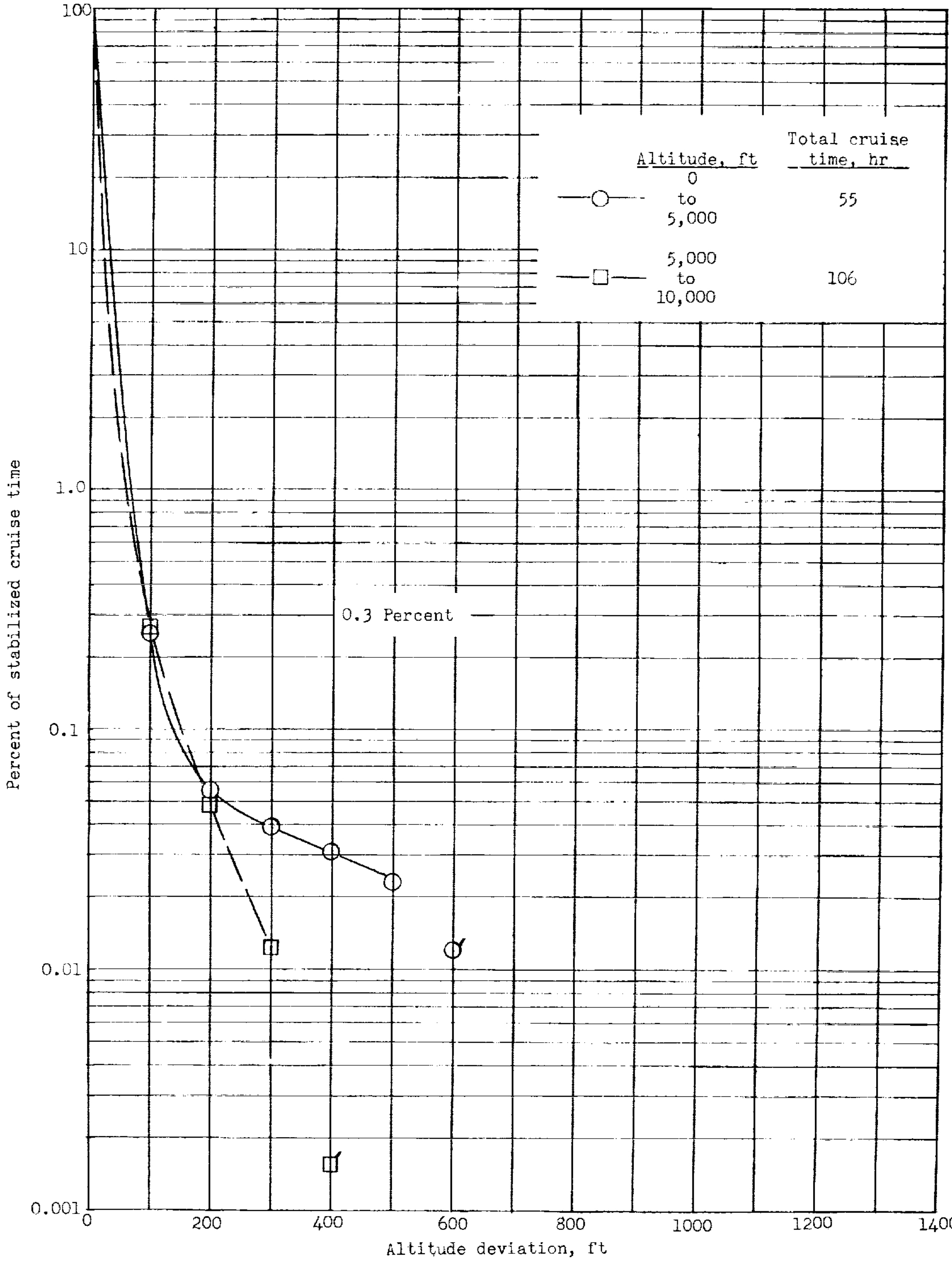

(n) Airplane VA; case 18.

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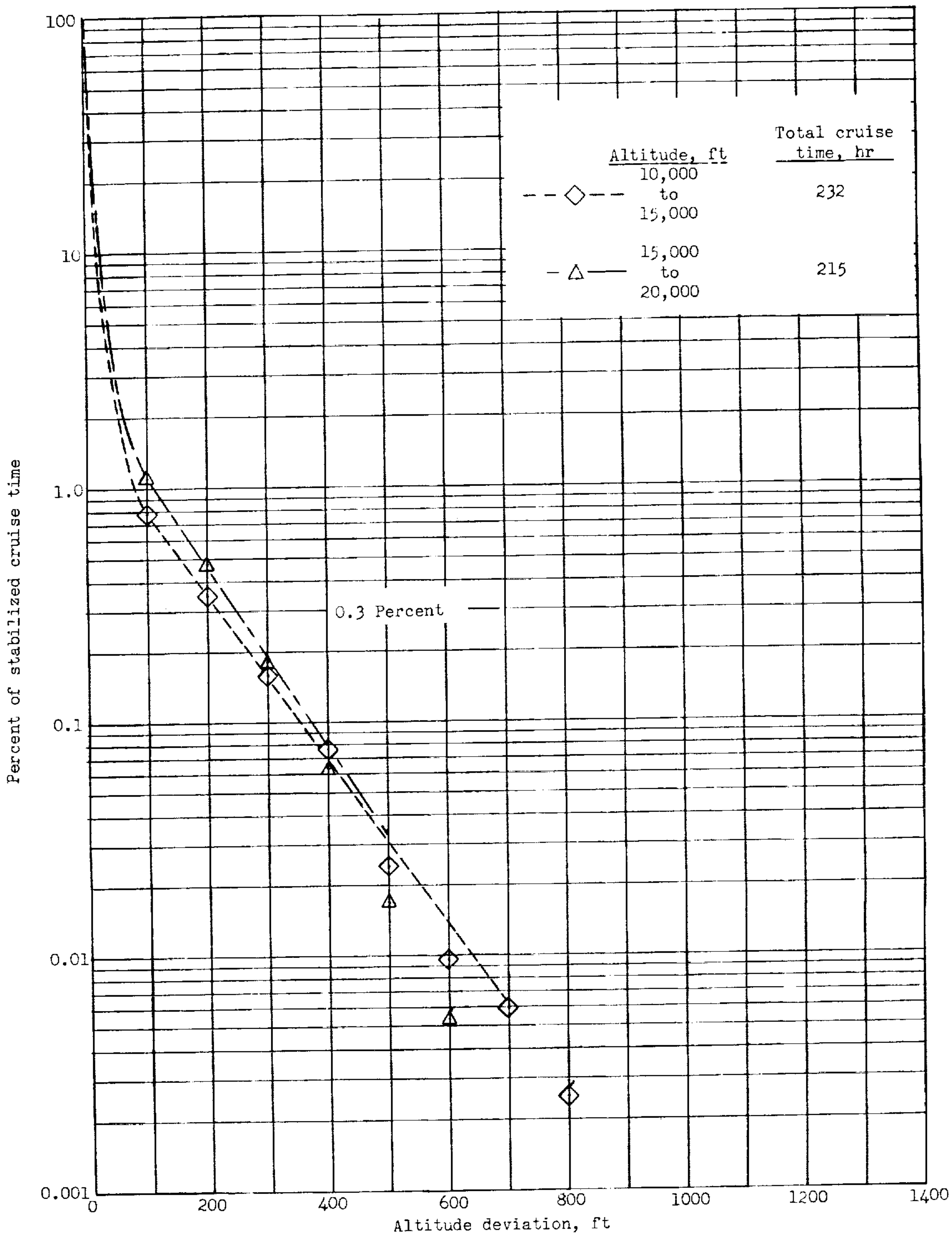

(o) Airplane VIA; case 19.

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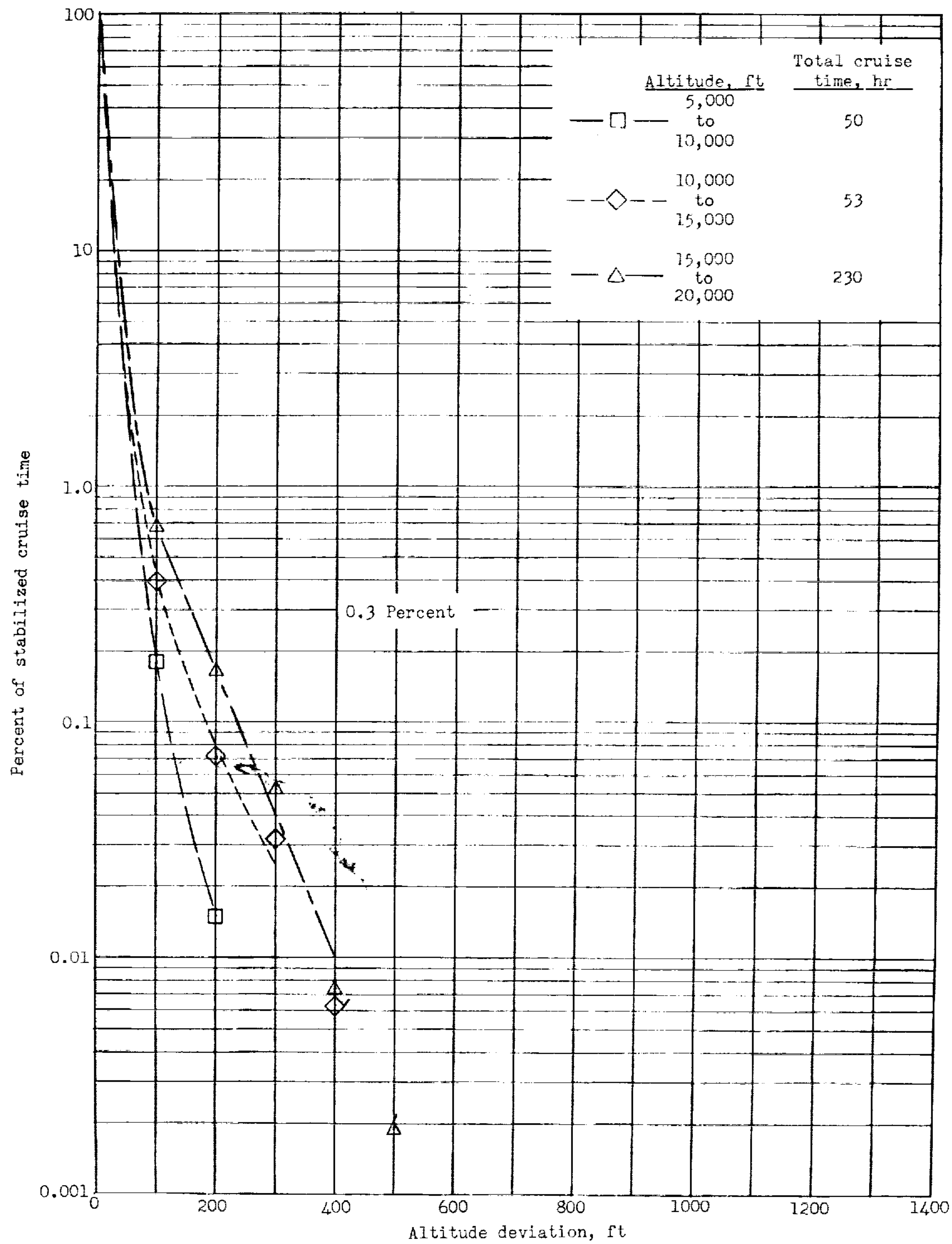

(p) Airplane X; case 20.

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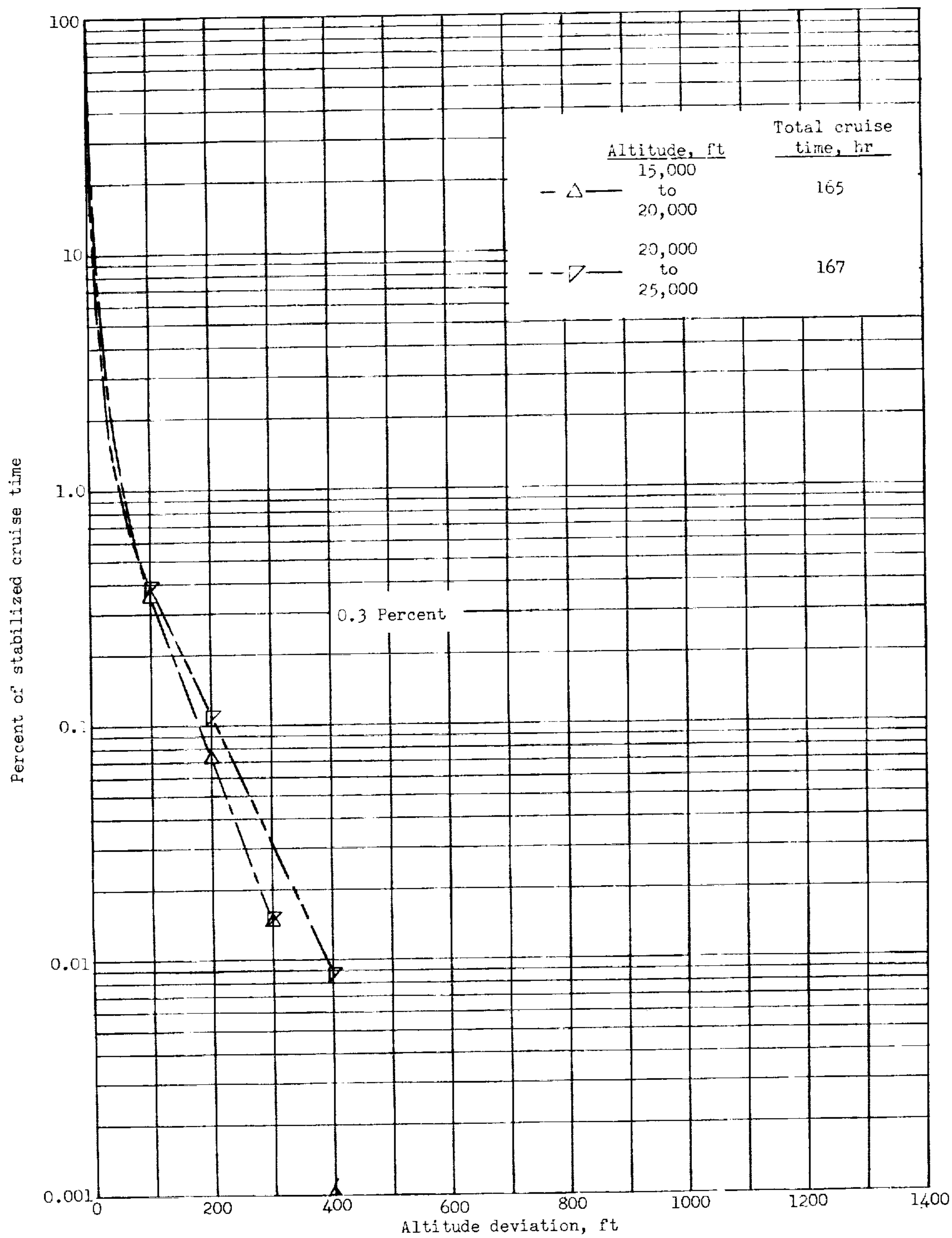

(q) Airplane XI; case 21.

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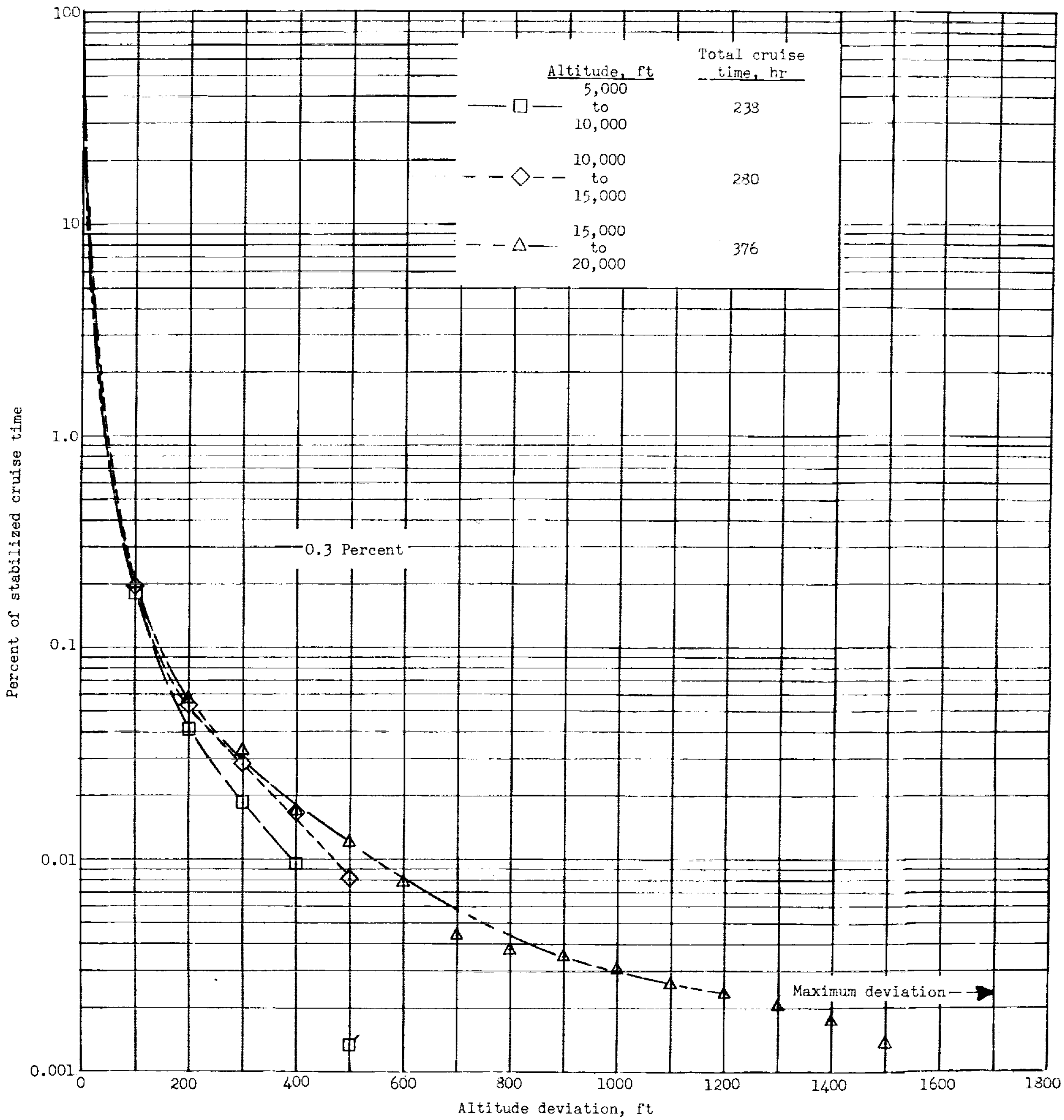

(r) Airplane XII; case 22.

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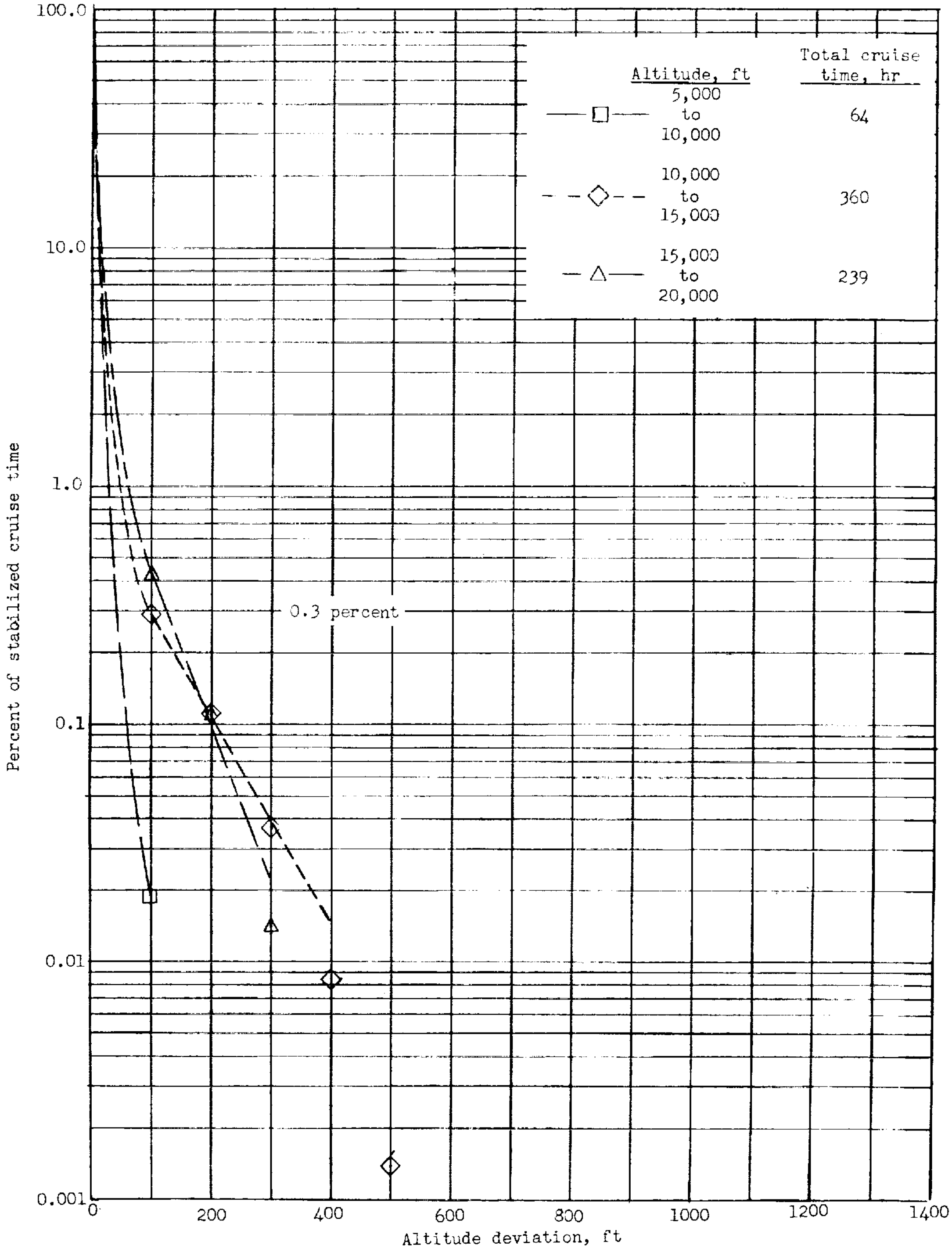

(s) Airplane XII; case 23.

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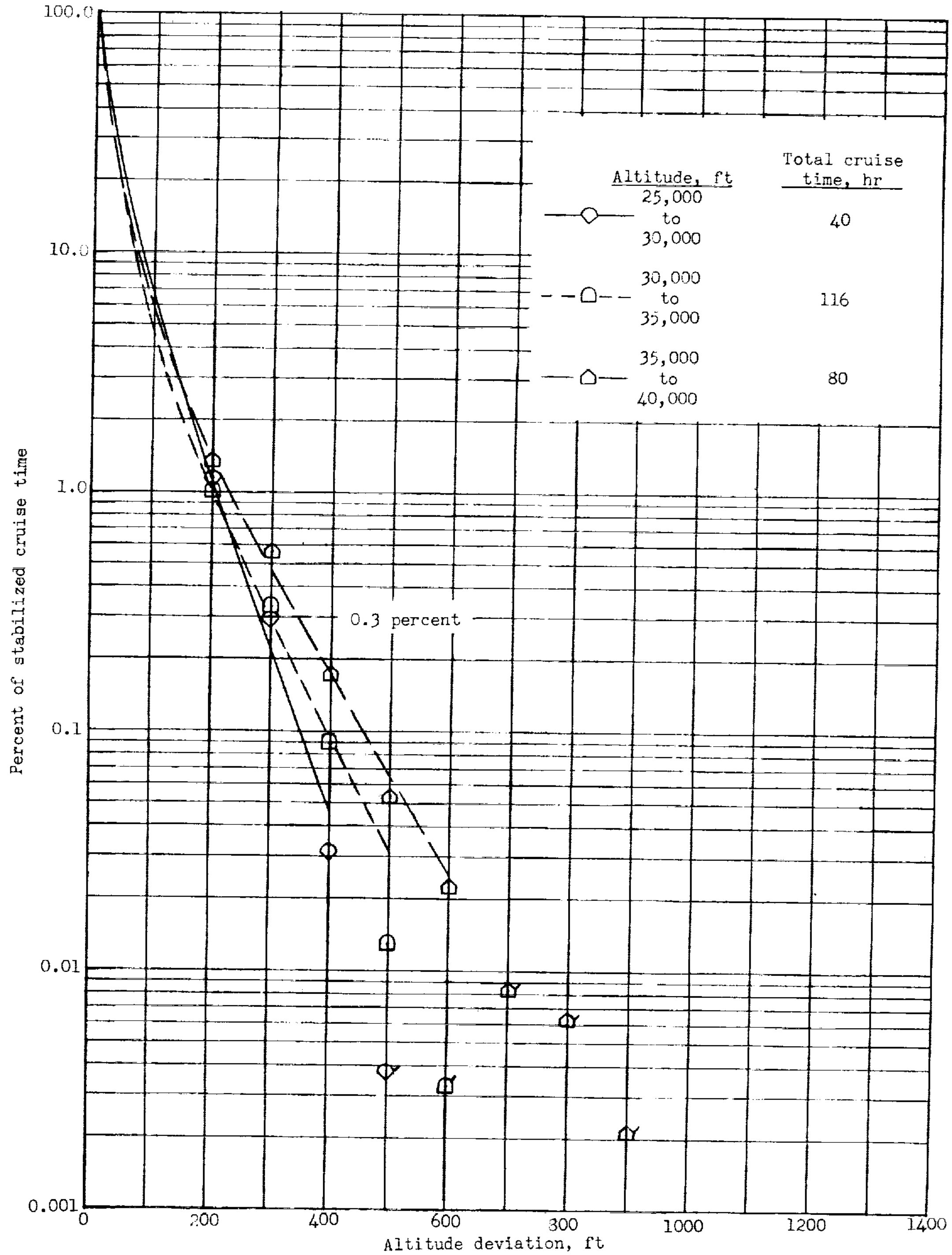
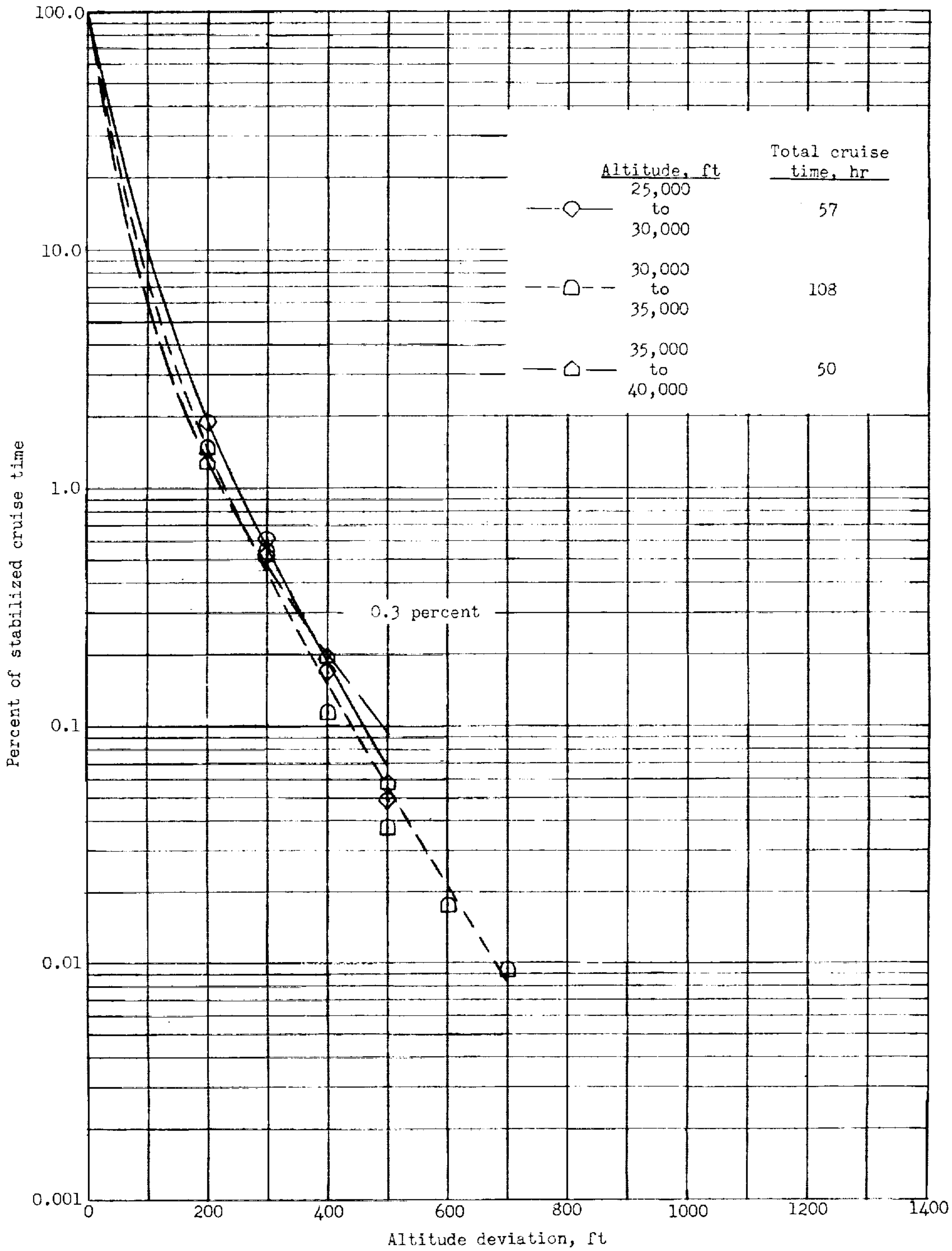


(a) Airplane IIIA; case 10.

Figure 3.- Percent of stabilized cruise time airplanes flew at or above various altitude deviations from stabilized cruise altitude for manual control. Flagged symbols denote data points for which time period was less than 0.5 minute.



(b) Airplane IIIA; case 12.

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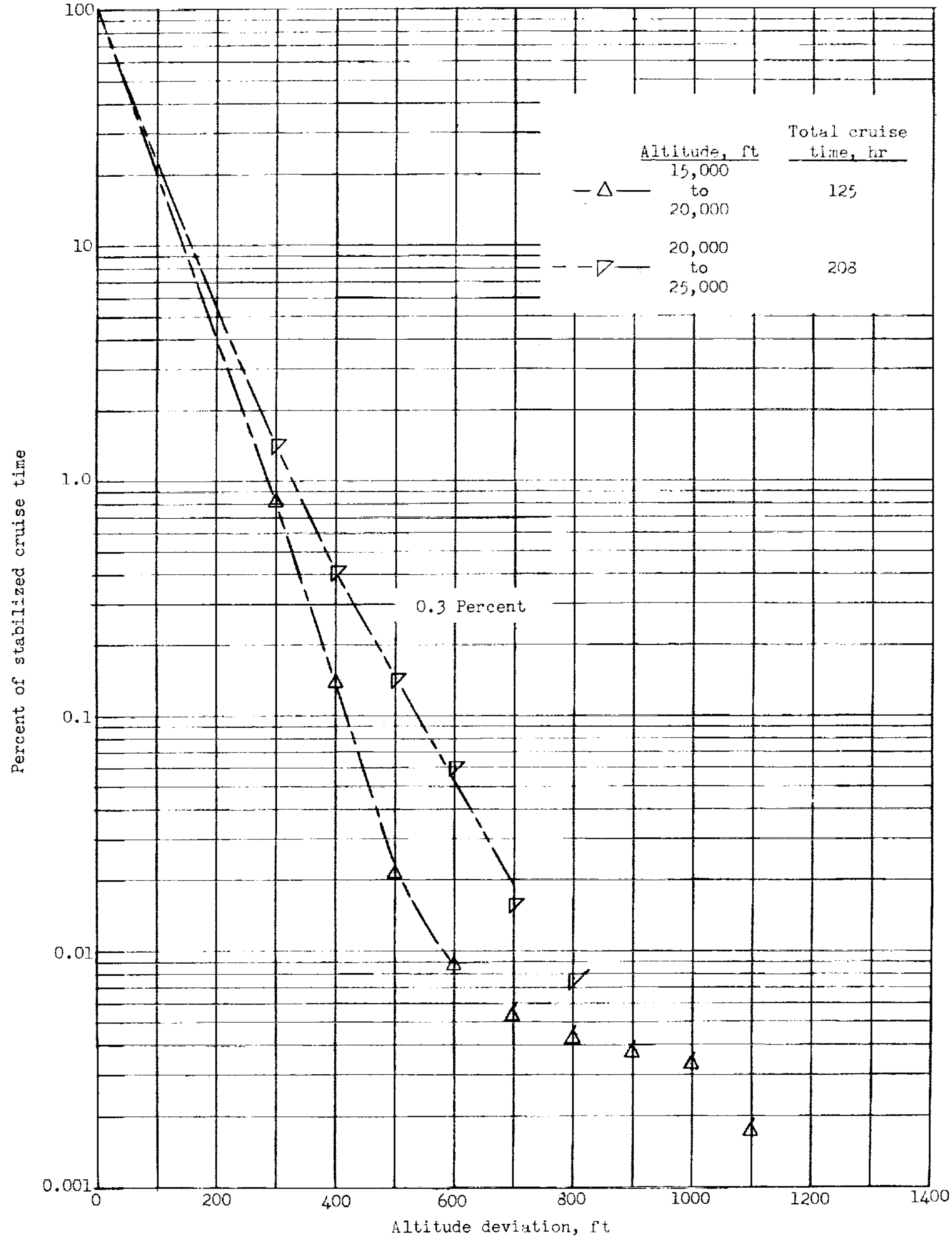
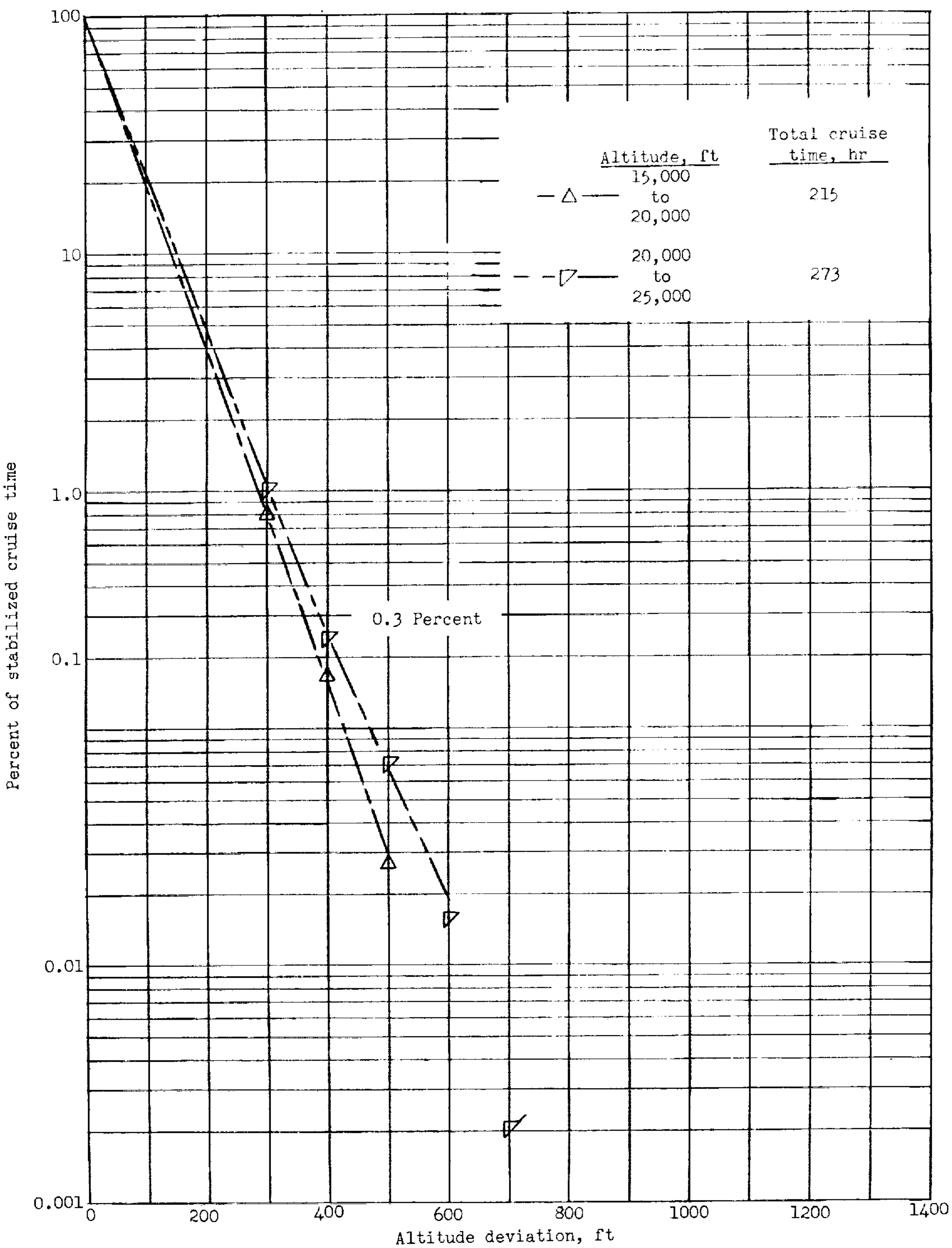


(c) Airplane IVA; case 14.

Figure 3.- Continued.



(d) Airplane IVA; case 16.

Figure 3.- Concluded.

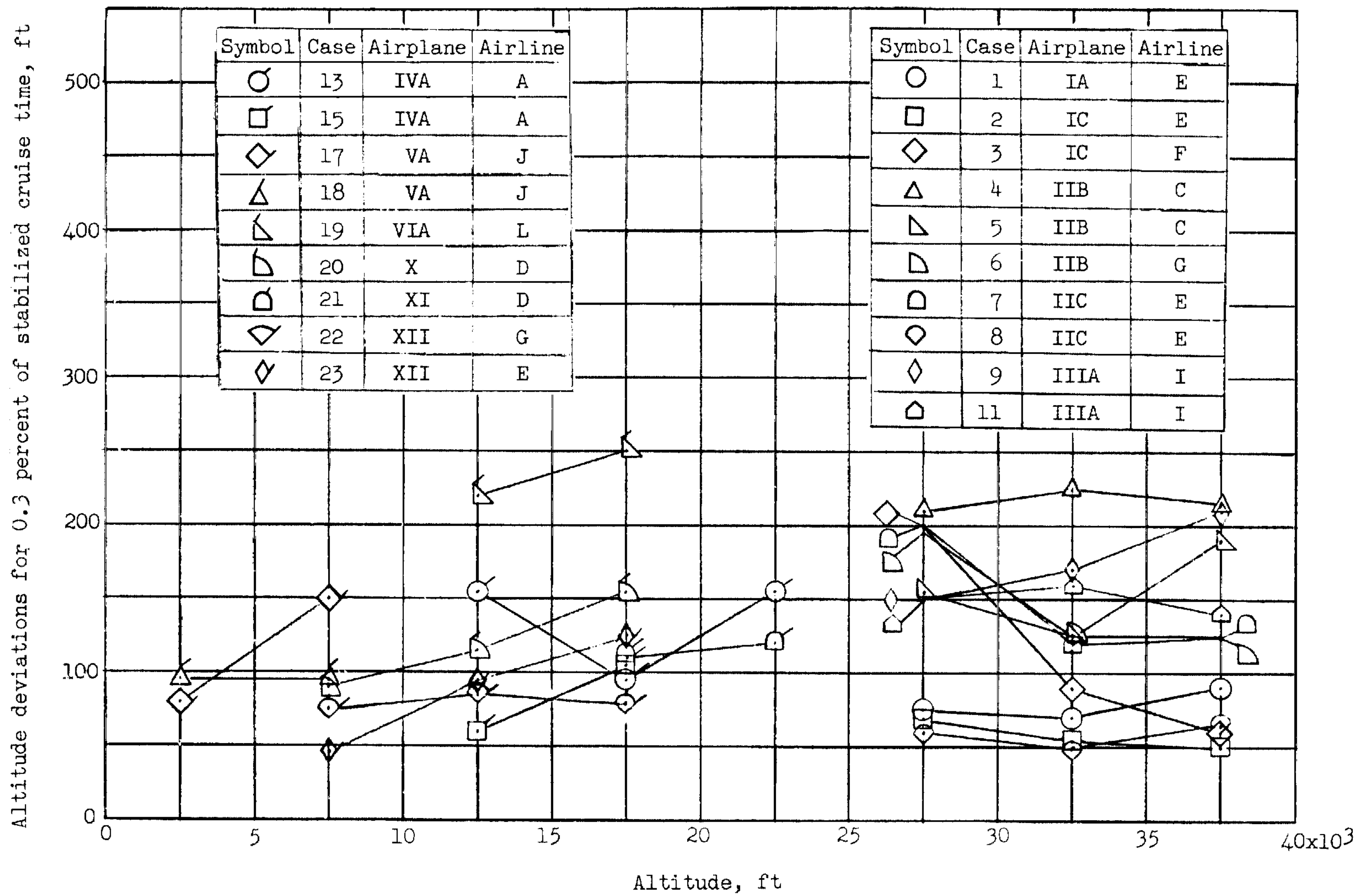
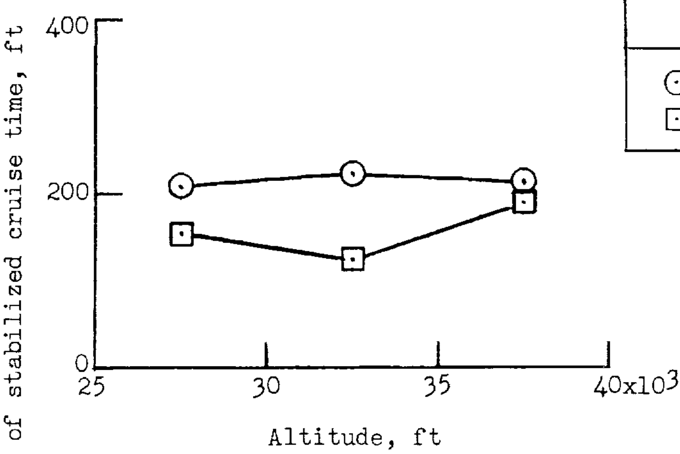
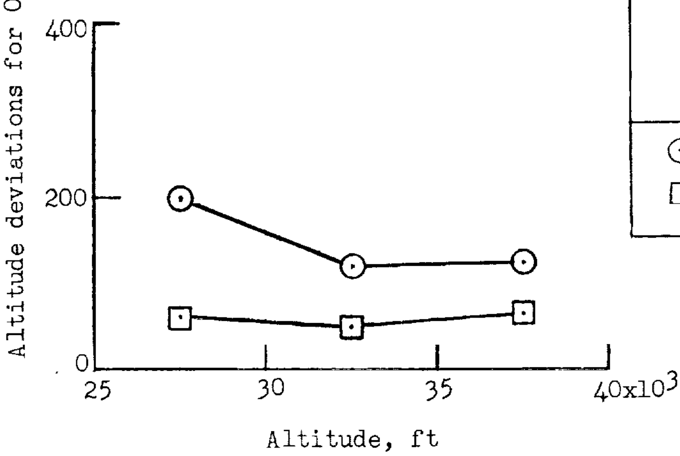


Figure 4.- Variation of altitude deviations for 0.3 percent of stabilized cruise time with altitude for 19 airplanes operated with autopilot in altitude-hold control.



	Case	Stabilized cruise time, hr		
		Altitude, ft		
		25,000 to 30,000	30,000 to 35,000	35,000 to 40,000
⊙	4	104	307	103
⊡	5	78	136	74

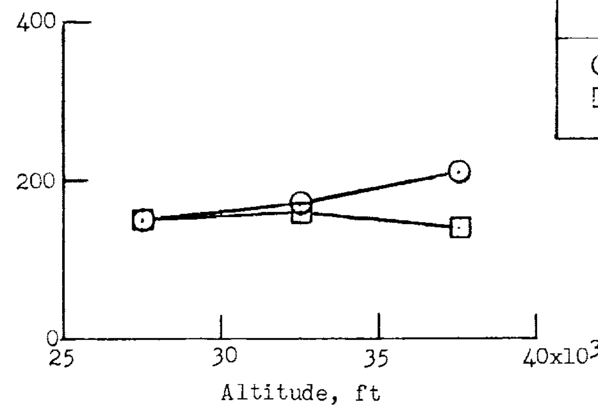
(a) Two type II airplanes operated by airline C.



	Case	Stabilized cruise time, hr		
		Altitude, ft		
		25,000 to 30,000	30,000 to 35,000	35,000 to 40,000
⊙	7	281	392	78
⊡	8	130	121	47

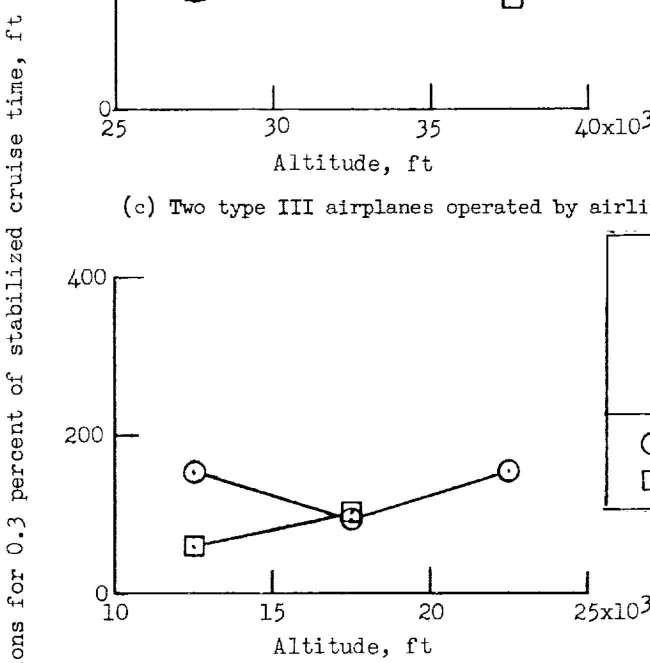
(b) Two type II airplanes operated by airline E.

Figure 5.- Variation of altitude deviations for 0.3 percent of stabilized cruise time with altitude for airplanes of the same type operated by the same airline over comparable routes; all data for operation with autopilot in altitude hold.



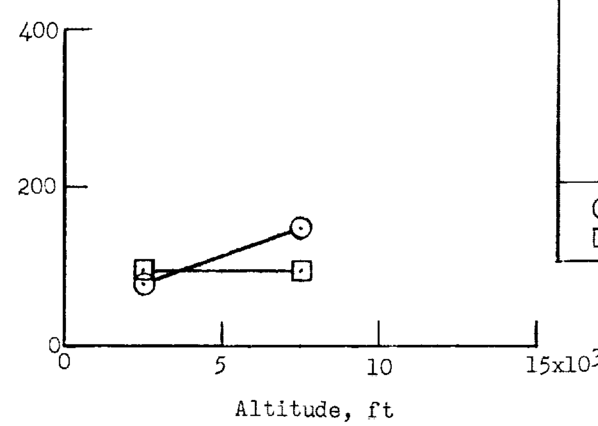
	Case	Stabilized cruise time, hr		
		Altitude, ft		
		25,000 to 30,000	30,000 to 35,000	35,000 to 40,000
⊙	9	90	218	134
⊡	11	101	168	86

(c) Two type III airplanes operated by airline I.



	Case	Stabilized cruise time, hr		
		Altitude, ft		
		10,000 to 15,000	15,000 to 20,000	20,000 to 25,000
⊙	13	113	315	137
⊡	15	58	101	---

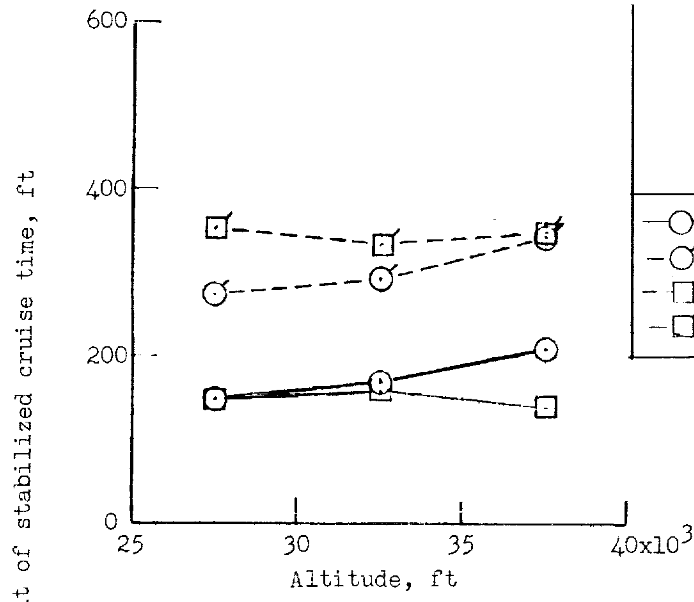
(d) Two type IV airplanes operated by airline A.



	Case	Stabilized cruise time, hr		
		Altitude, ft		
		0 to 5,000	5,000 to 10,000	10,000 to 15,000
⊙	17	59	94	---
⊡	18	55	106	---

(e) Two type V airplanes operated by airline J.

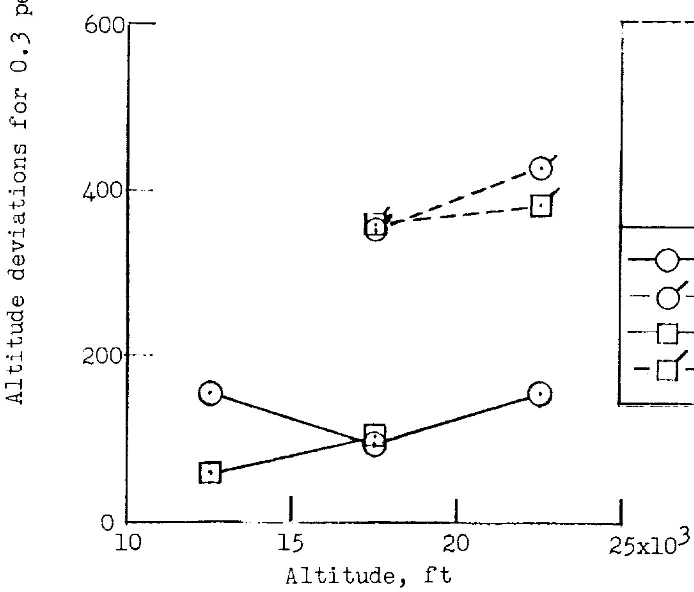
Figure 5.- Concluded.



	Case	Stabilized cruise time, hr Altitude, ft 25,000 to 30,000	 30,000 to 35,000	 35,000 to 40,000
	9	90	218	134
	10	40	116	80
	11	101	168	86
	12	57	108	50

---- Manual control
—— Autopilot control

(a) Two type III airplanes.



	Case	Stabilized cruise time, hr Altitude, ft 10,000 to 15,000	 15,000 to 20,000	 20,000 to 25,000
	13	113	315	137
	14	---	125	208
	15	58	101	---
	16	---	215	273

---- Manual control
—— Autopilot control

(b) Two type IV airplanes.

Figure 6.- Variation of altitude deviations for 0.3 percent of stabilized cruise time with altitude for airplanes operated with manual control and with autopilot in altitude hold.

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